RESEARCH MEMORANDUM

A COMPARISON OF FLIGHT-MEASURED CARRIER-APPROACH SPEEDS WITH VALUES PREDICTED BY SEVERAL DIFFERENT CRITERIA FOR 41 FIGHTER-TYPE AIRPLANE CONFIGURATIONS

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NATIONAL ADVISORY COMMITTEE
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RESEARCH MEMORANDUM- U.B.

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SUMMARY

Lift and drag characteristics have been determined in flight in the landing-approach configuration on 41 jet-propelled fighter-type airplane arrangements, including various wing boundary-layer-control installations. Minimum comfortable approach speeds for carrier-type landings were evaluated for these airplanes by four test pilots. The reason given most frequently for limiting (i.e., not reducing) approach speed was "inability to control altitude"; the reason given second most frequently was "stall proximity." For airplanes limited by altitude controllability, none of a number of simple criteria considered for predicting approach speed enabled predictions within ±5 knots for all the configurations. A criterion in which the approach speed was assumed to be 115 percent of the power-approach stalling speed gave as good agreement with flight values as any of the criteria considered. Departures from predicted approach speeds assumed to be 115 percent of the power-approach stalling speed were consistent with the presence of "secondary" favorable or unfavorable factors. For several of the airplanes, approach speeds were selected on the "back side" of the curve of thrust required against velocity, indicating that this condition does not of itself impose a limitation on the approach speed.

INTRODUCTION

In recent years pilots have tended to increase the landing speeds of modern jet-propelled fighter airplanes in relation to the stalling speeds. The higher landing speeds have, in turn, increased the requirements for landing gear and carrier arresting gear strength and for length of landing runway.

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Consequently, the Ames Aeronautical Laboratory of the NACA has undertaken a general program to study the problems associated with the landing approach. One of the objectives of this program is to develop means for reducing the landing speeds. To this end, studies have been made both in wind tunnels and in flight of various arrangements of boundary-layer-control (BLC) systems. As indicated in references 1 to 6 effective BLC can reduce stalling speeds, and since the landing-approach speed is, in a general way, related to the stalling speed, it is not surprising to find that the landing-approach speed was reduced correspondingly.

Another objective of the program is to identify the factors that contribute to the selection of a particular approach speed. Other reports have listed many of the factors which pilots believe could be the principal reasons for not reducing approach speeds below selected values (see, e.g., refs. 6 to 9). There still remains unsolved, however, the problem of relating these factors to the approach speed quantitatively. A third objective of the Ames program is, then, to develop satisfactory criteria for predicting approach speeds quantitatively. Extensive flight investigations which have been conducted in connection with this broad program have yielded a considerable amount of data. Data have been accumulated on the lift-drag characteristics of 41 fighter-type configurations, including various BLC arrangements. The minimum comfortable approach speeds in carrier-type approaches were selected by several pilots, and the reasons given by the pilots for not reducing the approach speeds below the selected values were also determined. Supplementary studies are being conducted on a landing-approach simulator to aid in developing approach-speed criteria (ref. 10).

The purposes of this report are to present the available lift-drag data, to show the applicability of various simple criteria for predicting carrier-approach speeds, and to summarize the reasons why pilots limit their approach speeds.

SYMBOLS

A_x longitudinal acceleration, units of gravity, g

A_z vertical acceleration, units of gravity, g

C_L lift coefficient, $\frac{\text{lift}}{qS}$

$C_{L_{max}}$ maximum lift coefficient

C_D drag coefficient, $\frac{\text{drag}}{qS}$

D drag, lb

F_G	gross engine thrust, lb
hp	horsepower
L	lift, lb
S	wing area, sq ft
T	thrust, lb
V	velocity, knots
W	weight of airplane, lb
W_a	mass flow of air through engine, slugs/sec
q	dynamic pressure, lb/sq ft
α	angle of attack, deg
δ_f	flap deflection, deg
ρ	atmospheric density, slugs/cu ft
γ	flight-path angle, radians
$\dot{\gamma}$	rate of change of flight-path angle, radians/sec

Subscripts

o	standard sea-level conditions
S	stall
PA	power approach
max	maximum
min	minimum
av	average
avail	available

INSTRUMENTATION

NACA recording instruments were used to record airspeed, altitude, vertical and longitudinal acceleration, angle of attack, and tail-pipe pressure. Standard calibration techniques were used for calibrating the recording airspeed systems for all the airplanes except the F9F-6, the F9F-4, the F-94C, and the F-84F airplanes; for these latter airplanes nose-boom installations providing static pressure sources about 10 feet ahead of the airplane nose were presumed to yield static pressure with no significant error. Indicated airspeeds were calibrated against recorded airspeeds for all configurations. For most of the configurations the single tail-pipe probe, which was used as a thrust indicator in accordance with the technique described in reference 11, was calibrated by use of a ground thrust stand; an exception was the F9F-4 for which, in the absence of a calibration, the tail-pipe probe was assumed to measure the average total head across the exit.

AIRPLANES

Ten airplanes were tested in the current program, the FJ-3, F4D, F7U-3, F9F-4, F9F-6, F-84F, F-86A, F-86F, F-94C, and F-100A. Two-view sketches of these airplanes are shown in figure 1. Various wing modifications were tested on a number of these airplanes including fences, different leading-edge arrangements (slats, cambered leading edges, and suction boundary-layer control), and different trailing-edge flap arrangements (blowing boundary-layer control and suction boundary-layer control). The particular arrangement used for each test configuration is indicated in table I. References describing the modifications in more detail, where available, are indicated in table I.

TESTS

The flight program consisted of tests to determine the lift and drag as a function of angle of attack for each configuration, and tests by several pilots to determine the carrier landing-approach speed. To obtain the lift and drag curves, data were recorded during runs in steady flight in the power-approach condition at a number of different airspeeds from about 200 knots down to about 10 knots above the stalling speed. A time history was then obtained from this speed to the stall. The rate of change of airspeed during the time history portion of the record did not exceed 1 knot per second. In the interest of safety the lift-drag tests were conducted at altitudes ranging from 5,000 feet to 10,000 feet.

For the pilot's evaluation of approach speed, carrier-type landing approaches were made. In this type of approach the airspeed is relatively constant, the flight-path angle is quite low (of the order of 0° to 2°), and a high level of engine power is required to maintain steady flight. The use of this technique permitted the pilots to quote a single value for the approach speed, in contrast to conditions in low-power sinking-type approaches where the airspeed may be changing throughout the approach. The technique employed by the pilots was to determine the stalling speed at a safe altitude, and then perform a series of approaches at progressively lower approach speeds at approach altitudes until the minimum comfortable speed had been determined. This value was determined by the pilot for a landing weight equal to the weight empty plus 1,000 pounds fuel per engine. The pilot also reported his reason for limiting the approach speed to the value designated. The tests were conducted at a field carrier-landing practice facility maintained by the Navy at Crows Landing, California.

For a few of the configurations, supplementary evaluations were made with the mirror-approach technique in which the pilot guides the airplane along a straight beam of light reflected from a mirror at an appropriate flight-path angle (about $3\text{-}1/4^{\circ}$).

Of the four NACA test pilots who participated in the evaluations, pilots A and D had no experience in landing aboard actual carriers. Pilot A is a veteran test pilot with Air Force fighter experience. Pilot D has had field training and practice for carrier landings as a Marine fighter pilot. Pilots B and C are experienced carrier pilots.

RESULTS

Presentation of Data

Aerodynamic characteristics.- Plots of angle of attack, drag coefficient, and lift-drag ratio versus lift coefficient, and of drag and power required for level flight versus velocity are shown in figures 2 to 42 for each of the 41 airplane configurations. The equations used for the determination of these curves from recorded flight data are as follows:

$$C_L = \frac{W(A_Z \cos \alpha + A_X \sin \alpha) - F_G \sin \alpha}{qS}$$

$$C_D = \frac{W(A_Z \sin \alpha - A_X \cos \alpha) + F_G \cos \alpha - 1.69 W_a V}{qS}$$

The curves of drag in level flight against velocity were determined from the relationships

$$D = C_D \frac{1}{2} \rho S V^2$$

$$V = \sqrt{\frac{W}{\frac{1}{2} \rho S (C_L + C_D \tan \alpha)}}$$

Based on the data shown in figures 2 to 42, a number of quantities pertinent to the estimation of approach speed have been determined and are tabulated in table II. These quantities are defined as follows:

$C_{L_{max}}$ values taken from figures 2 to 42

$V_{S_{C_{L_{max}}}}$ $\sqrt{\frac{W}{C_{L_{max}} \frac{1}{2} \rho S}}$

$C_{L_{max_{PA}}}$ $C_{L_{max}} + \left(C_{D_{o.8C_{L_{max}}}}\right)\left(\sin \alpha_{C_{L_{max}}}\right)$, maximum lift coefficient with first-order approximation for the effect of the thrust required for level flight

$V_{S_{PA}}$ $\sqrt{\frac{W}{C_{L_{max_{PA}}} \frac{1}{2} \rho S}}$

$V_{S_{pilot}}$ average carrier-approach stalling speed reported by pilots (The stalling speeds reported by the individual pilots are listed in table III.)

Approach speeds.- In table II the approach speeds predicted by various criteria are listed for all the configurations tested, and in table IV the minimum comfortable approach speeds selected by the individual pilots are listed, together with the average values for all the pilots. The average flight approach speeds are compared with the values predicted by several methods in figure 43, and the approach speeds for the individual pilots are compared with the predicted approach speeds in figures 44 to 51. For the few configurations (4a, 4b, 16a, 16b, 16c) for which the pilots established approach speeds using the mirror-approach technique as well as the landing-signal-officer technique, there were no significant differences in the approach speeds selected; the mirror-approach values are, therefore, not presented here.

The term "minimum comfortable approach speed" as used in this report should be interpreted as the lowest trimmed approach speed which the pilot would deliberately use. It is not the absolute minimum, which is considered to be that speed below which emergency thrust application is needed or the landing approach is aborted. In fact, some speed fluctuations about the minimum comfortable approach speed would be anticipated as a result of attitude changes to adjust altitude. So long as the speed decrease was not too rapid, and the actual value of the speed reduction did not exceed about 5 knots in these maneuvers, the pilot would not feel urgently impelled to return the speed to the trim value. This value of 5 knots may vary somewhat for different configurations, depending on the rate of development of limiting factors and the severity of the limiting factors.

DISCUSSION

Methods for the Prediction of Minimum Comfortable Approach Speed

Stall-speed method.- A number of different methods have been advanced in the past for predicting approach speeds. The most commonly used methods have assumed the approach speed to be a certain percentage of the stalling speed, say 115 percent. A given value for this ratio of approach speed to stalling speed represents a fixed lifting acceleration available for changing flight-path angle, or alternatively a fixed margin of speed above the stall. These methods of predicting approach speed give no consideration to the speed changes that would occur if the throttle were not used in conjuction with the longitudinal control in maneuvering. Several of the criteria of this class considered here differ from each other only in the definition of the stalling speed used.

(a) For $1.15\ V_{S_{C_{L_{max}}}}$ the stalling speed is based on the aerodynamic $C_{L_{max}}$ (taken from figs. 2 to 42) with no allowance for the thrust contribution to lift.

(b) For $1.15\ V_{S_{PA}}$ the stalling speed is based on the addition to the aerodynamic $C_{L_{max}}$ of a first-order estimate of the thrust contribution to the lift. This first-order lift increment is calculated on the assumption that thrust is equal to the drag at the approach speed, the approach speed, in turn, being assumed to occur at 0.8 $C_{L_{max}}$ or at about 0.75 $C_{L_{max_{PA}}}$. The lift increment due to thrust is then computed as:

$$\Delta C_{L_{PA}} = \left(C_{D_{o.8C_{L_{max}}}}\right)\left(\sin \alpha_{C_{L_{max}}}\right)$$

(c) For 1.15 $V_{S_{pilot}}$ the stalling speed is based on the average stalling speed reported by the pilots. This value was examined as an additional criterion to cover the possibility that the pilots may regard the effective stalling speed as other than the speed corresponding to the maximum lift coefficient. This condition could result from the difficulty in defining the stall as discussed subsequently, or from possible disparities in the amount of thrust effect that should be included in the definition of maximum lift (thrust for level flight at V_S as against thrust for level flight at V_{PA}, for example). Figure 52 shows a comparison of the average values of V_S reported by the pilots with the values of V_S corresponding to $C_{L_{max_{PA}}}$. The results show that, except for four configurations (6b, 8a, 8b, 12a), the average stalling speeds reported by the pilots agree with computed values within 3-1/2 knots. Considering the readability of airspeed indicators and other factors which make precise determination of stalling speeds difficult (note the dispersion in the values for the individual pilots in table III), this agreement is good verification of the validity of the method of estimating $C_{L_{max_{PA}}}$ previously described.

On some of the airplane designs included in this study the manifestations which usually identify a stall occurred only after the airplane had decelerated through a range of speeds wherein other characteristics were deteriorating progressively. The gradually worsening stability and control characteristics or the increase in sink rate with decreasing speed may reach such levels that the pilot considers the airplane "stalled" at a speed higher than the actual stall speed and accordingly limits his operating range to this speed rather than the true stalling speed. Of the configurations listed in table I, the following were indicated by the pilots to have this stall approach characteristic:

Airplane	Configuration	Deteriorating characteristic
F4D	4a, 4b	Sink rate, lateral-directional characteristics
F7U-3	5a, 5b	Sink rate
F-84F	8a, 8b	Sink rate, lateral-directional characteristics
F-86F (modified)	12b	Lateral-directional characteristics
F-100A	16a, 16b, 16c	Sink rate, lateral-directional and longitudinal characteristics

velocity for zero rate of climb

It is noteworthy that the four airplanes for which sink rate was a deteriorating characteristic had curves of drag against velocity that exhibited an extended range of speeds for which the airplane could fly on a steep back side of the curve (figs. 10, 11, 12, 13, 17, 18, 30, 40, 41, and 42). This characteristic would, of course, make for an increase in sink rate with decreasing speed.

Method based on $\dot{\gamma} = 0.060$.- This criterion differs from those previously listed in that it stipulates a fixed capability of producing rate of change of flight-path angle rather than a fixed lifting acceleration capability. The expression for predicting the approach speed for this criterion is developed in Appendix A. It was previously indicated that a fixed ratio of V_{PA}/V_S implied a given value of $\Delta A_{z_{avail}}$. From the basic relationship $\Delta A_Z = V\dot{\gamma}$, it is apparent that assumption of a fixed ability to change flight-path angle, $\dot{\gamma}$, will result in calculating greater ratios of approach speed to stalling speed, V_{PA}/V_S, for higher values of stalling speed V_S.

McDonnell method.- A refinement of the criteria listed previously is provided by the McDonnell criterion described in reference 12 which incorporates the effects of drag characteristics. This criterion defines the approach speed as that speed at which a 50-foot climb can be performed with specified conditions of lift and speed changes and with no addition of thrust during the maneuver.

Speed-stability method.- This criterion is simply represented as the speed for minimum drag. The usual variations of drag in level flight with airspeed are such that if the effects of stick-free and stick-fixed longitudinal stability are disregarded, the speed for minimum drag will represent a speed for neutral speed stability, separating a stable region at higher speeds from an unstable region at lower speeds; that is, at speeds higher than that for minimum drag the airplane will return to the trim speed following a disturbance; at lower speeds the airplane will diverge in speed following a disturbance.

With regard to this criterion, reference 13 points out that the minimum drag point loses its significance as a point of neutral speed stability when all the longitudinal degrees of freedom are considered. It is noted further, however, that if the airplane motion is constrained to a constant altitude or to a rectilinear flight path, then the minimum drag point again regains its significance. This constraint condition appears to be a reasonable one to apply to the landing-approach situation, in which case the speed for minimum drag would be the appropriate speed to define neutral speed stability.

Method based on speed for maximum L/D.- The speed for maximum L/D may be significant as a criterion in view of the fact that it is the speed corresponding to minimum glide angle, considering only aerodynamic parameters. For this reason it is included among the criteria evaluated herein.

Method based on speed for minimum power required.- This speed was considered as having possible significance as an indicator of the speed for minimum rate of descent at zero thrust. A factor of 1.08 was used with this speed in order to provide the best agreement between flight approach speeds and the speeds predicted by this method from present tests.

Reasons for Limiting Approach Speed

A number of different terms are used by the pilots as reasons for limiting the approach speed. These are defined more completely in the following section:

(a) Ability to control altitude - Some difficulty has been experienced in defining this reason explicitly, apparently because a number of factors may combine in different ways to produce different airplane responses, all of which the pilot describes by this reason. If the individual factors that produce the response could be isolated, it is possible that this reason would break down into a number of different reasons, each more descriptive than the broader term. As of this time it has not been possible to isolate all the individual factors, and the following description of ability to control altitude must, therefore, be broad enough to reflect the combined effects of all the factors. The term "ability to control altitude" and such synonymous terms as "ability to arrest sink" and "longitudinal control of flight path" are used to describe the condition where there is unsatisfactory response of the airplane to attempts to gain altitude or to produce positive flight-path angle changes. The unsatisfactory altitude controllability has in an isolated instance been identified with deficient response of the airplane to longitudinal control, due to control ineffectiveness, but, in general, as already noted, the responsible factors have not been segregated. The deficient altitude controllability may be, but is not necessarily, associated with large rates of airspeed loss. The throttle may be used in conjuction with aerodynamic controls in maneuvering the airplane to define the altitude controllability, the amount of throttle depending on the relative response of the airplane to aerodynamic and thrust control, and perhaps even more on the inclination of the pilot to rely on the throttle. (This difference in pilot attitude toward reliance on the throttle is, for example, believed to be responsible for some of the disagreements between approach speeds quoted by the Ames test pilots.) However, some aerodynamic maneuvering capability is required by all pilots, and most of them seem to treat aerodynamic control as the dominant control.

In the study reported in reference 9, the predominant reason for limiting approach speed was deterioration of speed stability. Since, in many of the cases studied in the present investigation, rapid changes in airspeed were associated with development of unsatisfactory altitude controllability, it is probable that the reason given in reference 9 corresponds to the general category of reason described herein as "ability to control altitude."

(b) Stall proximity - This term is used to describe the condition where, maneuvering characteristics and all other characteristics of the airplane being satisfactory, the pilot is forced to limit speed because of either stall behavior or stall warning. A stall that was characterized by an abrupt pitching or rolling tendency with inadequate warning might define the speed above which a certain speed margin is demanded by the pilot in the approach; or the existence of stall warning in the form of buffeting, mild pitch-up, or similar controllable motions at speeds well removed from the stall might cause the pilot to select even higher approach speeds, while indicating stall proximity to be the reason for limiting approach speed.

(c) Unsatisfactory lateral-directional (stability or control) characteristics - The development of erratic or unusual lateral-directional stability or control characteristics may prevent the pilot from following a desired precise flight course. If these characteristics occurred at a lift coefficient considerably removed from $C_{L_{max}}$, so that they would not tend to be identified with the stalling of the wing, then the pilot might use this term as the reason for limiting approach speed.

(d) Visibility - In steady flight, pitch attitudes attained may be so high that it would be difficult for the pilot to see the landing signal officer or other ground references that the pilot is accustomed to using. In such cases "visibility from the cockpit" would be given as the reason for limiting approach speed.

<u>Reasons in combination</u>.- In some cases approach speeds are described as being limited for other reasons in combination with ability to control altitude (table IV). One possible interpretation for such a case is that either factor alone would have limited the approach speed at the selected value. Another interpretation is that the presence of a number of factors in combination results in a higher approach speed than any one of the factors alone. There is not sufficient information in hand to provide a definitive answer as to which interpretation is correct, or even to state that only one interpretation is generally correct. There is evidence from one case that the presence of a number of factors results in higher approach speeds. The F4D airplane in configurations 4a and 4b had nearly

identical lift-drag characteristics, but the lateral-directional characteristics of configuration 4b were reported to be considerably worse than those of configuration 4a. Both configurations were described as limited in approach speed primarily by ability to control altitude although the selected approach speeds differed by about 9 knots. The accepted explanation of this paradoxical result is that the attention required of the pilot in controlling lateral-directional disturbances diverts him from the task of monitoring airspeed and flight-path changes so that an additional speed margin is desired.

Of the reasons listed for limiting approach speed, the most prevalent were ability to control altitude and stall proximity. Most of the criteria discussed herein are related to some extent to ability to control altitude. The approach speed of airplanes limited primarily for other reasons would not be expected to be as closely predicted by these criteria. In the comparisons in figures 43 to 51, different symbols are used to distinguish these latter airplanes from those limited by ability to control altitude.

Comparison of Flight and Predicted Approach Speeds

Because of a number of factors, it is considered that the values given for the individual and average flight approach speeds can be relied on only within about 2 knots at best. One source of uncertainty is the fact that pilots cannot, with assurance, report approach speed to the nearest knot; in fact, there is a definite tendency to round the value off to the nearest 5 knots. Ability to read the airspeed indicator to a given increment would be a factor in this regard, as would ability to define a comfortable speed within narrow limits. Differences in evaluation standards among individual pilots would exist even for skilled test pilots and could only be partially compensated for by averaging results. There are recognized differences in control technique among pilots which might also contribute to individual differences. The effects of all these factors are demonstrated by the inconsistency of the differences among various pilots shown by the data in table IV.

To arrive at a figure that would represent acceptable scatter in the comparison of flight and predicted approach speeds, the foregoing factors were borne in mind. An additional factor considered is the existence of secondary reasons for limiting approach speed, discussed in a previous section of this report. With all these factors in mind, it appears that an acceptable criterion would be one that predicted approach speeds within ±5 knots of the average flight value for all applicable configurations.

Inspection of the curves of figure 43 indicates that none of the criteria were successful in predicting approach speeds within ±5 knots for all configurations. For the bulk of the data the best levels of agreement were obtained with the 1.15 $V_{S_{PA}}$ criterion and a modified form of the McDonnell criterion; the modification, not included in the plotted data, was the subtraction of 2 knots from the speed calculated by the basic criterion, this 2-knot reduction being over and above a 2-knot reduction that was already applied in accordance with the McDonnell method to approximate the effect of thrust on the value of $C_{L_{max}}$. An equivalent level of agreement was also obtained with the 1.15 $V_{S_{pilot}}$ criterion. However, values of the pilots indicated stalling speed are not available for all the configurations, so that the conclusions regarding the validity of this criterion would be less general. The $\dot{\gamma}$ criterion appeared to be better than the other criteria for the airplanes that approach at higher speeds, but was somewhat less consistent for the main body of the data.

The other criteria considered gave less satisfactory correlation with flight values. In particular, the speed stability criterion, V for minimum drag, was shown by several configurations to be inapplicable; for configurations 4a, 4b, 5a, 5b, and 16a, the selected approach speed fell on the back side of the drag-velocity curves, well removed from the speed for minimum drag. This fact is noteworthy since flight on the back side of the curve in the landing approach has long been considered impractical.

The foregoing comparisons indicate that none of the simple criteria considered here enabled predictions to be made within the acceptable limits of ±5 knots. Until such a criterion is developed it would appear that a reasonable procedure to use in predicting approach speeds would be the use of one of the criteria that gave the best level of agreement, say 1.15 $V_{S_{PA}}$, with the understanding that certain secondary factors might increase or decrease the approach speeds. This general procedure, which is suggested by the comparative results for the F4D airplane (configurations 4a and 4b) discussed earlier, appears to be consistent with the pilots' concepts of the manner in which approach speeds are determined.

To implement this procedure it would be desirable to be able to associate certain numerical increments in approach speed with certain degrees of severity of the secondary factors. The pilots did not feel that they could segregate the effects of the various secondary factors to produce a quantitative correlation. The present data do, however, show consistent qualitative effects which are indicated here. Generally, these factors influence approach speed to the degree that they prevent the pilot from maneuvering with the minimum of attention to monitoring airspeed or altitude. Detrimental factors that would tend to cause increased approach speeds are unfavorable stability and control characteristics, poor visibility from the cockpit, insufficient engine thrust available for maneuvering, or a sharp increase in unstable slope of the drag-velocity curve. As indicated earlier, when these factors become sufficiently pronounced they may be identified as limiting the approach speed. When they are less severe they may simply modify upward the approach speed predicted by the criterion that defines ability to control altitude.

There are, on the other hand, favorable secondary factors which tend to reduce the approach speeds. On the basis of data in figure 43 for the $1.15\ V_{S_{PA}}$ criterion, for example, it would appear that operative boundary-layer control installations which are powered by bleed air from the primary thrust source reduce approach speeds by amounts greater than would be predicted from the change in V_S, the average reduction amounting to about 3 knots. Similarly, it appears that a margin of thrust available for maneuvering of the order of $\Delta T/W = 0.3$ may reduce approach speeds below the level predicted by the criterion.

Other factors may evoke a favorable comment from the pilots, such as good stick-fixed or stick-free longitudinal stability, favorable trim changes with speed or throttle movement, etc. However, at the present time the relative importance of all these factors remains to be established.

Comparison of Test Pilots' and Service Pilots' Approach Speed

The minimum approach speeds presented in this report were obtained by skilled test pilots under relatively favorable conditions of field landings. It is of interest to compare the test values with the approach speed recommended for service pilots. The following table compares the test approach speeds with values recommended in pertinent service publications for the few configurations for which such data are available. Median values of the approach speeds used by fleet pilots in actual carrier operations, as determined from unpublished statistical measurements, are also shown for the two airplanes for which such data are available. Also, since the relationship of the maximum approach speed to the median approach speed is of concern for structural design purposes, the distributions of measured approach speeds as determined from the statistical measurements, are shown for these two airplanes (fig. 53). The latter data are corrected to the landing weights used in the present investigation.

Configuration	Airplane	Test carrier-type approach, knots	Minimum recommended service value, knots	Fleet value, knots	Reference for recommended service value	Service type of landing
1	FJ3	112	115	121	AN-01-60JKC-1	Carrier
5a	F7U-3	107	117	122[a]	AN-01-45HFD-1A	Carrier
7	F9F-6	114	117	---	AN-01-85FGD-1	Carrier
4a	F4D	121	123	---	AN-01-40FBA-1	Carrier
16a	F-100A	149 to 161	Final 181 Touchdown 148	---	TO-1F-100A-1	Field
15a	F-94C	131	Final 144 Touchdown 119	---	TO-1F-94C-1	Field
8a	F-84F	132	Over fence 159	---	TO-1F-84F-1	Field

[a]This value is higher than the mean service value given for the same airplane in reference 10. The difference is ascribed to the fact that the data in reference 10 were obtained from service test pilots who were intent on approaching at slow speeds.

The tabulated results and the data in figure 53 indicate that the approach speeds from the present evaluations are consistently lower than the service-recommended values (which, in turn, are lower than the fleet values). The amounts by which the test values differ from the recommended service values range from about 2 knots to 10 knots for the Navy airplanes. For the Air Force airplanes, assuming, as suggested in reference 6, that the "over-the-fence" speed is equivalent to the carrier-approach speed, and assuming arbitrarily that the "over-the-fence" speed is about 10 knots higher than the touchdown speed, the differences are less consistent, but tend to show even greater departures from the test values. The larger differences between test and service values correspond to the existence of secondary factors of pronounced degree; in the case of the Air Force airplanes, difference in type of approach (field versus carrier) may also be a contributing factor.

CONCLUSIONS

Lift and drag characteristics have been determined in flight in the landing-approach configuration on 41 jet-propelled fighter-type airplane arrangements, including various wing boundary-layer-control installations. Minimum comfortable approach speeds for carrier-type landings were evaluated for these configurations by four test pilots. Flight approach speeds for the various configurations ranged from 92 to 157 knots, but the bulk of the data on which the conclusions are based were in the speed range of 95 to 115 knots. As a result of these evaluations the following conclusions were reached:

1. The reason most frequently given by the pilots for limiting approach speeds was inability to control altitude; the reason given second most frequently was stall proximity.

2. None of a number of simple criteria examined enabled prediction of approach speeds within ±5 knots for all configurations limited primarily by altitude controllability. A criterion in which the approach speed was assumed to be 115 percent of the power approach stalling speed ($1.15\ V_{S_{PA}}$) gave as good agreement with flight values as any of the criteria considered.

3. Departures from predicted approach speeds based on taking $1.15\ V_{S_{PA}}$ were consistent with the presence of "secondary" factors. Favorable secondary factors were indicated to be large thrust margins and operative boundary-layer-control installations that are powered by bleed air from the primary thrust source. (Operation of the boundary-layer control resulted in approach-speed reductions larger than the stalling-speed reductions.) Unfavorable secondary factors included deficient flying qualities characteristics, meager thrust margin, and poor visibility from the cockpit.

4. When unfavorable factors become pronounced at higher speeds, they may become the primary reasons for limiting approach speed, in which case the approach speed would be more than 5 knots higher than would be predicted by $1.15\ V_{S_{PA}}$.

5. Recommended approach speeds from service manuals tend to be higher than the minimum comfortable approach speeds of the present evaluations. The amount of the difference seems to depend on the strength of unfavorable secondary factors.

6. The necessity to fly on the back side of the curve of thrust required against velocity does not of itself impose a limitation on the approach speed. However, the limiting conditions under which such flight is possible remain to be defined.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Dec. 11, 1957

APPENDIX A

DEVELOPMENT OF EQUATION FOR PREDICTING APPROACH SPEED FOR CONSTANT VALUE OF $\dot{\gamma}$

At a constant speed equal to the approach speed the vertical acceleration available for maneuvering is given by

$$\Delta A_Z = \frac{1.69\ V_{PA}\dot{\gamma}}{g} = \frac{\Delta C_L \frac{\rho}{2} S V_{PA}^2}{W} \tag{A1}$$

where

$$\Delta C_L = C_{L_{max}} - C_{L_{PA}} \tag{A2}$$

or

$$\Delta C_L = \frac{W}{S}\left(\frac{1}{q_S} - \frac{1}{q_{PA}}\right) \tag{A3}$$

Substituting equation (A3) for ΔC_L in equation (A1), one obtains the following expression for $\dot{\gamma}$

$$\dot{\gamma} = \frac{V_{PA}g}{1.69}\left(\frac{1}{V_S^2} - \frac{1}{V_{PA}^2}\right) \tag{A4}$$

If the terms are rearranged, an equation relating V_{PA}, V_S, and $\dot{\gamma}$ is found as follows:

$$V_{PA}^2 - 1.69\ \frac{\dot{\gamma}}{g}\ V_S^2 V_{PA} - V_S^2 = 0 \tag{A5}$$

A value of $\dot{\gamma}$ of 0.060 was found to provide the best general level of agreement between flight approach speeds and the value of V_{PA} as computed from equation (A5); this value of $\dot{\gamma}$ was used in the comparison curves of this report.

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TABLE I.- CONFIGURATIONS OF TEST AIRPLANES

Configuration no.	Airplane	Landing weight, including 1000 lb fuel per engine, lb	Wing area, sq ft	W/S, lb/sq ft	Speed brakes	Flap type	Flap setting, deg	Wing L.E. configuration and flow control devices	BLC type	Operation of BLC	$\left(\frac{\Delta T}{W}\right)_{avail}$	Ref. report	Figure number for data
1	FJ-3	13,678	288	47.5	Out	Slotted	45	15° Slat	None	---	0.34	1	2
2a	FJ-3	13,850	288	48.1	Out	Plain	55	15° Slat	Suction flap	On	.31	1	3
2b	FJ-3	13,850	288	48.1	Out	Plain	55	15° Slat	Suction flap	Off	.31	1	4
2c	FJ-3	13,850	288	48.1	In	Plain	55	15° Slat	Blowing flap	On	.33	1	5
3a	FJ-3	13,990	302	46.4	In	Plain	55	Extended camber, and fence	Blowing flap .02 nozzle	On	.32	1	6
3b	FJ-3	13,990	302	46.4	In	Plain	55	Extended camber, and fence	Blowing flap .01 nozzle	On	.33	1	7
3c	FJ-3	13,990	302	46.4	In	Plain	55	Extended camber, and fence	Suction flap	On	.34	1	8
3d	FJ-3	13,990	302	46.4	In	Plain	55	Extended camber, and fence	Blowing flap	Off	.35	1	9
4a	F4D[1]	16,870	557	30.3	In	None	---	10° Slat	None	---	.30	---	10
4b	F4D[2]	17,260	557	31.0	In	None	---	2-300 Gal. tanks 10° slat	None	---	.30	---	11
5a	F7U-3	21,030	535.3	39.3	In	None	---	Slat	None	---	.14	---	12
5b	F7U-3	21,030	535.3	39.3	Out	None	---	Slat	None	---	.13	---	13
6a	F9F-4	13,100	250	52.4	In	Plain	Outboard 45 Inboard 40	Leading-edge flap	Blowing flap	On	.22	2	14
6b	F9F-4	13,100	250	52.4	In	Plain	Outboard 45 Inboard 40	Leading-edge flap	Blowing flap	Off	.22	2	15
7	F9F-6	13,440	300	44.8	In	Plain	Outboard 30 Inboard 40	Slats	None	---	.24	---	16
8a	F-84F	15,636	325	48.2	In	Plain	40	Plain	None	---	.15	---	17
8b	F-84F	15,636	325	48.2	Out	Plain	40	Plain	None	---	.13	---	18
9a	F-86A	12,192	288	42.3	In	Plain	55	15° Slat	Suction flap	On	.25	3,6	19
9b	F-86A	12,192	288	42.3	In	Plain	55	15° Slat	Suction flap	Off	.24	3,6	20
9c	F-86A	12,192	288	42.3	In	Plain	64	15° Slat	Suction flap	On	.23	3,6	21
9d	F-86A	12,192	288	42.3	In	Plain	64	15° Slat	Suction flap	Off	.24	3,6	22
10a	F-86A	12,335	294	42.9	In	Plain	55	Camber	Suction flap	On	.23	3,6	23
10b	F-86A	12,335	294	42.9	In	Plain	55	Camber	Suction flap	Off	.23	3,6	24
11a	F-86A	12,335	294	42.9	In	Plain	55	Camber, fence	Suction flap	On	.23	3,6	25
11b	F-86A	12,335	294	42.9	In	Plain	55	Camber, fence	Suction flap	Off	.24	3,6	26
11c	F-86A	12,335	294	42.9	Out	Plain	64	Camber, fence	Suction flap	On	.23	3,6	27
11d	F-86A	12,335	294	42.9	Out	Plain	64	Camber, fence	Suction flap	Off	.25	3,6	28
12a	F-86F	12,900	288	44.75	Out	Slotted	38	Plain	Suction L.E.	On	.23	4,6	29
12b	F-86F	12,900	288	44.75	Out	Slotted	38	Plain	Suction L.E.	Off	.20	4,6	30
13a	F-86F	12,860	288	44.70	Out	Plain	55	15° Slat	Blowing flap	On	.19	5	31
13b	F-86F	12,860	288	44.70	Out	Plain	55	15° Slat	Blowing flap	Off	.20	5	32
13c	F-86F	12,860	288	44.70	In	Plain	66	15° Slat	Blowing flap	On	.19	5	33
13d	F-86F	12,860	288	44.70	In	Plain	66	15° Slat	Blowing flap	Off	.20	5	34
14a	F-86F	12,860	302	42.6	In	Plain	55	Slatted 6-3	Blowing flap	Off	.23	5	35
14b	F-86F	12,860	302	42.6	In	Plain	55	Slatted 6-3	Blowing flap	On	.21	5	36
14c	F-86F	12,860	302	42.6	In	Slotted	38	Slatted 6-3	None	---	.24	5	37
15a	F-94C	14,933	233	64.10	In	Split	45	Plain	None	---	.21	---	38
15b	F-94C	14,933	233	64.10	Out	Split	45	Plain	None	---	.19	---	39
16a	F-100A	21,970	400	55.0	In	Plain	0	15° Slat	Blowing flap	Off	.14	---	40
16b	F-100A	21,970	400	55.0	In	Plain	45	15° Slat	Blowing flap	Off	.09	---	41
16c	F-100A	21,970	400	55.0	In	Plain	45	15° Slat	Blowing flap	On	.04	---	42

[1]External fuel tanks off.
[2]External fuel tanks on.

TABLE II.- AERODYNAMIC DATA AND CARRIER LANDING APPROACH-SPEED CRITERIA FOR EACH CONFIGURATION

Configuration no.	$C_{L_{max}}$	$V_{S_{C_{L_{max}}}}$, knots	$C_{L_{max_{PA}}}$	$V_{S_{PA}}$, knots	$V_{S_{pilot}}$, knots	Predicted landing approach speed for each criterion, knots								BLC type	Operation of BLC	
						$1.15\ V_{S_{C_{L_{max}}}}$	$1.15\ V_{S_{PA}}$	$1.15\ V_{S_{pilot}}$	McDonnell	$V_{\dot{\gamma}=0.050}$	$V_{D_{min}}$	$V_{(L/D)_{max}}$	$1.08\ V_{hp_{min}}$			
1	1.35	101.9	1.41	99.6	96.0	117.2	114.5	110.4	115.1	116.4	109	113.3	111.2	None	—	112
2a	1.44	99.0	1.52	96.5	96.7	113.9	111.0	111.2	113.7	112.4	109	113.6	110.2	Suction flap	On	107
2b	1.37	101.6	1.44	99.0	97.7	116.8	113.9	112.4	116.5	115.8	113.5	121.6	112.9	Suction flap	Off	109
2c	1.54	96.1	1.61	94.1	92.0	111.5	108.2	105.8	109.7	109.2	105	105.6	103.1	Blowing flap	On	103
3a	1.58	93.0	1.65	91.2	92.7	106.9	104.9	106.6	107.6	105.3	108.5	106.2	101.5	Blowing flap	On	102
3b	1.52	95.0	1.58	93.0	92.0	109.3	107.0	105.8	109.0	107.7	105.0	110.0	101.0	Blowing flap	On	104
3c	1.37	99.8	1.42	98.2	97.7	114.8	112.9	112.4	113.8	114.7	112.0	118.1	113.9	Suction flap	On	106
3d	1.30	102.6	1.36	100.3	98.3	118.0	115.4	113.0	115.9	117.6	118.0	121.1	115.0	Blowing flap	Off	111
4a	.80	106.0	.87	102.0	—	121.9	117.3	—	126.6	119.8	151.9	154.3	139.3	None	—	121
4b	.80	107.0	.87	103.0	—	123.1	118.5	—	129.8	121.2	165.0	163.2	148.5	None	—	130
5a	1.27	95.5	1.37	91.8	92.5	109.8	105.6	106.4	114.0	106.2	150+	—	136.0	None	—	108
5b	1.19	98.5	1.29	94.6	92.5	113.3	108.8	106.4	114.8	109.9	112.0	120.3	113.4	None	—	108
6a	2.32	81.5	2.44	79.6	81.0	93.7	91.5	93.1	97.8	90.3	96.0	100.5	92.3	Blowing flap	On	92
6b	2.02	87.4	2.12	85.3	90.5	100.5	98.1	104.1	103.3	97.7	106.0	106.9	99.9	Blowing flap	Off	103
7	1.43	96.2	1.51	93.5	90.0	110.6	107.5	103.5	113.7	108.4	115.8	121.2	116.1	None	—	119
8a	.95	122.0	.99	120.0	113.5	140.3	138.0	130.5	135.1	145.2	133.4	137.5	136.6	None	—	132
8b	.95	122.0	.99	120.0	113.5	140.3	138.0	130.5	136.7	145.2	132.2	138.1	138.8	None	—	132
9a	1.51	91.0	1.57	89.1	—	104.7	102.5	—	104.6	102.6	105.0	105.3	99.5	Suction flap	On	103
9b	1.48	92.0	1.54	89.9	—	105.8	103.4	—	105.8	103.7	109.0	113.4	104.8	Suction flap	Off	109
9c	1.55	89.7	1.62	87.7	—	103.2	100.9	—	103.6	100.8	96.0	100.5	98.3	Suction flap	On	100
9d	1.47	92.0	1.53	90.2	—	105.8	103.7	—	106.0	104.1	107.2	109.5	102.0	Suction flap	Off	106
10a	1.69	85.5	1.77	83.6	—	98.3	96.1	—	100.4	95.3	100.0	103.5	95.6	Suction flap	On	104
10b	1.51	90.5	1.58	88.5	—	104.1	101.8	—	104.3	101.7	105.0	110.1	99.9	Suction flap	Off	111
11a	1.42	93.3	1.47	91.7	91.7	107.3	105.5	105.5	106.6	105.9	101.2	104.2	102.1	Suction flap	On	107
11b	1.36	95.3	1.41	93.6	94.8	109.6	107.6	109.0	109.8	108.4	110.0	112.3	111.8	Suction flap	Off	113
11c	1.43	93.0	1.48	91.4	—	107.0	105.1	—	106.1	105.5	99.0	102.4	102.6	Suction flap	On	103
11d	1.33	96.4	1.37	95.0	—	110.9	109.3	—	110.3	110.3	108.4	111.2	110.7	Suction flap	Off	111
12a	1.79	85.9	1.89	83.5	89.0	98.8	96.0	102.4	102.1	95.4	111.4	116.6	105.3	Suction L.E.	On	107
12b	1.10	109.4	1.14	107.4	106.3	125.8	123.5	122.2	122.5	127.5	121.0	122.5	124.7	Suction L.E.	Off	130
13a	1.58	91.5	1.65	89.4	88.5	105.2	102.8	101.8	104.8	103.0	90.4	94.7	96.7	Blowing flap	On	98
13b	1.40	97.3	1.47	94.7	92.5	111.9	108.9	106.4	110.7	110.0	102.3	104.9	104.8	Blowing flap	Off	111
13c	1.59	91.2	1.67	88.8	—	104.9	102.1	—	105.0	102.2	90.5	92.6	95.6	Blowing flap	On	98
13d	1.44	95.9	1.50	93.7	—	110.3	107.8	—	109.9	108.7	103.0	111.6	105.3	Blowing flap	Off	111
14a	1.42	94.0	1.47	92.5	91.7	108.0	106.4	105.5	107.7	107.1	103.8	106.4	106.4	Blowing flap	Off	105
14b	1.59	88.8	1.65	87.1	86.0	102.1	100.2	98.9	102.5	100.0	93.0	96.6	97.2	Blowing flap	On	96
14c	1.41	94.0	1.47	92.5	89.7	108.0	106.4	103.1	108.6	107.1	117.5	119.4	109.1	None	—	106
15a	1.49	112.6	1.54	110.6	110.7	129.5	127.2	127.3	125.2	131.9	123.8	126.6	124.2	None	—	131
15b	1.44	114.5	1.49	112.6	110.7	131.5	129.5	127.3	126.4	134.8	120.0	120.8	124.7	None	—	131
16a	1.07	120.4	1.16	115.5	—	138.5	132.8	—	143.0	138.4	173.5	186.2	154.0	Blowing flap	Off	157
16b	1.14	116.5	1.23	112.3	—	134.0	129.1	—	137.3	133.9	150.0	157.8	139.9	Blowing flap	Off	145
16c	1.26	110.9	1.36	106.7	—	127.5	122.7	—	129.5	126.1	145.0	151.0	127.0	Blowing flap	On	134

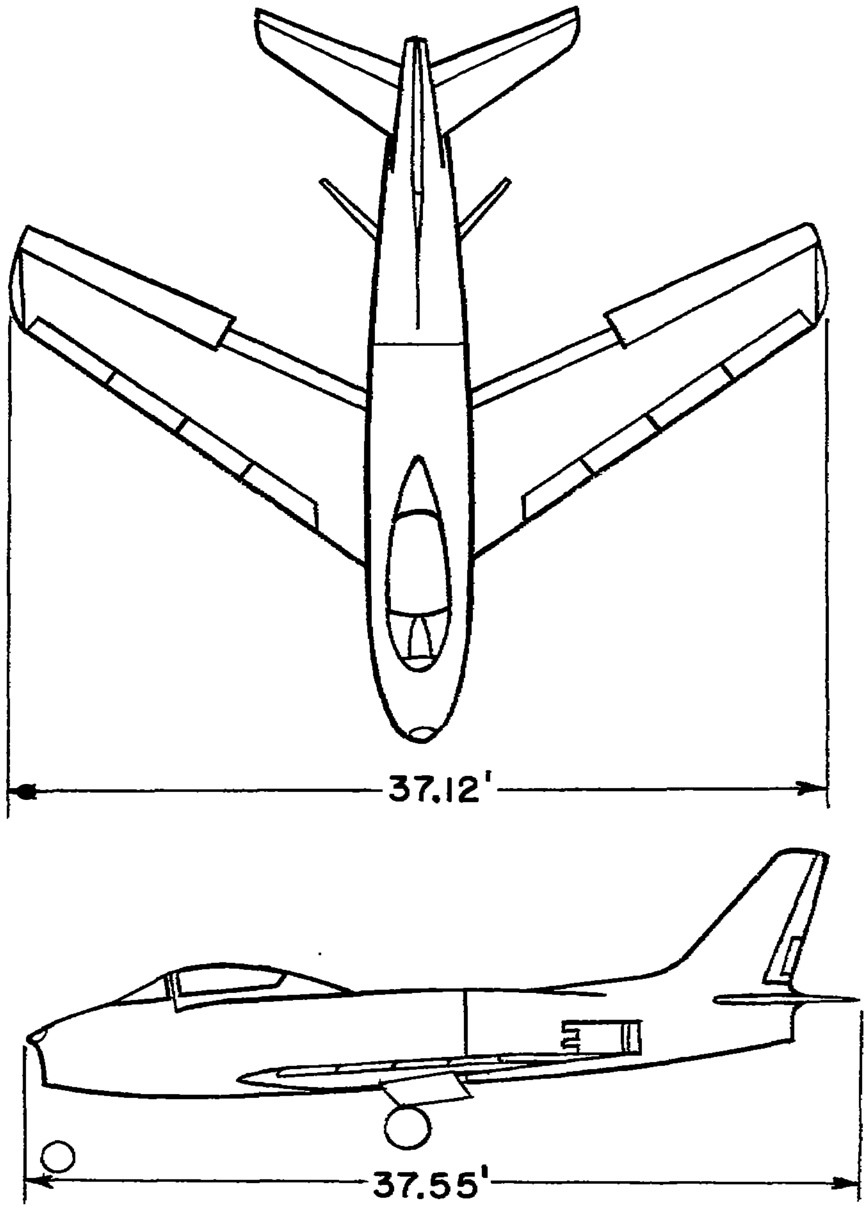
TABLE III.- FLIGHT DETERMINED STALLING SPEED

Configuration no.	Calibrated stalling speed, knots					Configuration no.	Calibrated stalling speed, knots				
	Individual pilots				Average of pilots, $V_{S_{pilot}}$		Individual pilots				Average of pilots, $V_{S_{pilot}}$
	A	B	C	D			A	B	C	D	
1	96	96	96	---	96.0	10a	---	---	---	---	---
2a	---	95	97	98	96.7	10b	---	---	---	---	---
2b	---	96	98	99	97.7	11a	90	92	89	96	91.7
2c	---	92	---	---	92.0	11b	94	95	94	96	94.8
3a	94	92	92	---	92.7	11c	---	---	---	---	---
3b	91	92	93	---	92.0	11d	---	---	---	---	---
3c	99	95	99	---	97.7	12a	92	86	90	88	89.0
3d	102	98	95	---	98.3	12b	112	97	112	104	106.3
4a	---	---	---	---	---	13a	88	88	88	90	88.5
4b	---	---	---	---	---	13b	93	92	92	93	92.5
5a	90-95	95	90	---	92.5	13c	---	---	---	---	---
5b	90-95	95	90	---	92.5	13d	---	---	---	---	---
6a	82	77	81	84	81.0	14a	90	93	92	---	91.7
6b	90	90	90	92	90.5	14b	85	86-88	86	---	86.0
7	88	93	89	---	90.0	14c	89	89	91	---	89.7
8a	114	110-114	114	114	113.5	15a	113	109	110	---	110.7
8b	114	110-114	114	114	113.5	15b	113	109	110	---	110.7
9a	---	---	---	---	---	16a	---	---	---	---	---
9b	---	---	---	---	---	16b	---	---	---	---	---
9c	---	---	---	---	---	16c	---	---	---	---	---
9d	---	---	---	---	---						

TABLE IV.- CARRIER LANDING-APPROACH SPEEDS AND REASONS FOR LIMITING AS DETERMINED FROM FLIGHT EVALUATIONS

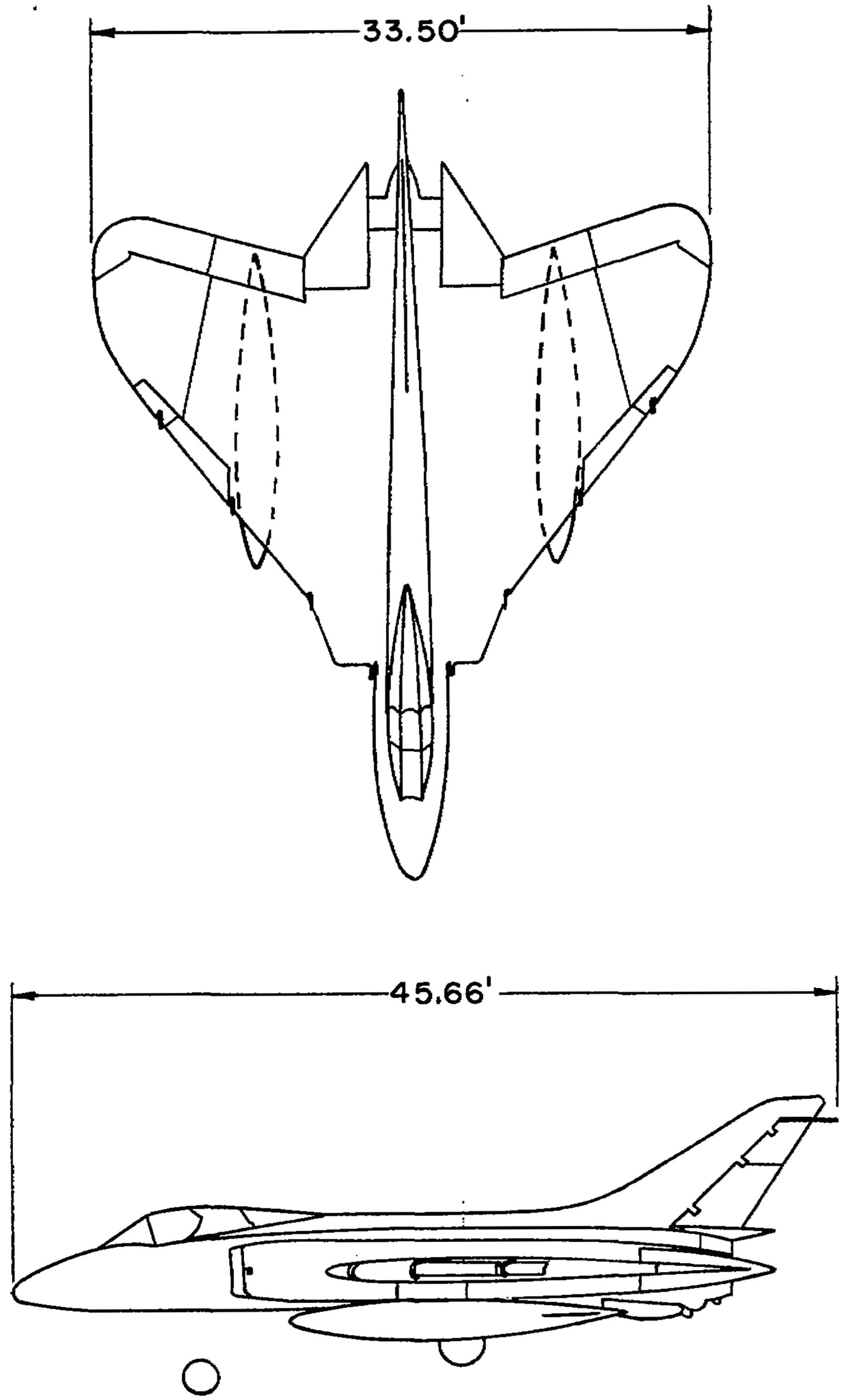
Configu-ration no.	Calibrated approach speed, knots, and primary reason for limiting approach speed — Individual pilots: A	B	C	D	Average of pilots: Approach speed, knots	Reason for limiting approach speed: Primary	Secondary	Remarks
1	[1]113	[1]111	[1]113	---	112	(1)	---	Powerful thrust margin contributes to improved altitude controllability.
2a	---	[2]106	[2]106	[2]106	107	(2)	---	
2b	---	[2]108	[1]110	[2]108	109	(2)	(1)	
2c	[1]102	[1]104	[1]103	---	103	(1)	---	
3a	[2]103	[2]102	[2]102	---	102	(2)	---	
3b	[2]105	[2]102	[2]105	---	104	(2)	---	
3c	[2]107	[1]109	[2]107	---	108	(2)	(1)	
3d	[2]112	[2]109	[2]112	---	111	(2)	(1)	
4a	[1]120	[1]118	[1]124	[1]122	121	(1)	(3)	Poor lateral-directional characteristics at low speeds affect approach speed. Powerful thrust margin.
4b	[1]135	[1]128	[1]130	[1]125	130	(1)	(3)	Lateral-directional characteristics considered even worse with tanks on than with tanks off. Powerful thrust margin.
5a	[1]107	[1]107	[1]109	---	108	(1)	---	ΔT/W marginal at gross weights greater than those of present evaluation.
5b	[1]107	[1]107	[1]109	---	108	(1)	---	Same as configuration 5a.
6a	[1]95	[2]87	[1]96	[1]91	92	(1)	(2,4,3)	
6b	[1]103	[1]100	[1]107	[1]100	103	(1)	(4)	
7	[1]114	[1]114	[1]114	---	114	(1)	(3)	Poor lateral-directional characteristics at low speeds objectionable. Effect on approach speed uncertain.
8a	[1]130	[1]130	[1]136	[1]133	132	(1)	(2,3)	Airplane yaws abruptly during flare. Elevator control force characteristics poor.
8b	[1]130	[1]130	[1]136	[1]133	132	(1)	(2)	Same as configuration 8a.
9a	[1]103	[1]98	[1]105	[1]104	103	(1)	---	
9b	[1]110	[1]105	[1]112	[1]108	109	(1)	---	
9c	[1]100	[1]100	---	[1]101	100	(1)	---	
9d	[1]105	[1]108	---	[1]105	106	(1)	---	
10a	[1]103	[1]99	[1]108	[1]105	104	(1)	---	
10b	[1]110	[1]105	[1]115	[1]113	111	(1)	---	
11a	[1]108	[1]102	[1]106	[2]112	107	(1)	(5)	
11b	[1]115	[1]108	[1]115	[2]112	113	(1)	(5)	
11c	[1]102	[1]102	[1]107	[2]102	103	(1)	(5)	
11d	[1]110	[1]111	[1]115	[2]109	111	(1)	(5)	
12a	[5]107	[1]103	[5]112	[1]107	107	(5)	(1)	Ability to control altitude and visibility from cockpit were of approximately equal importance in defining approach speed.
12b	[2]129	[2]129	[2]129	[2]134	130	(2)	---	Airplane yaws abruptly during flare.
13a	[2]98	[1]97	[2]99	98	98	(2)	(1)	
13b	[1]111	[1]111	[1]112	[1]108	111	(1)	---	
13c	[2]98	[1]97	[2]99	[1]98	98	(2)	---	
13d	[1]111	[1]111	[1]112	[1]108	111	(1)	---	
14a	[2]103	[2]101	[1]110	---	105	(2)	(1,3)	
14b	[2]95	[2]96	[2]97	---	96	(2)	(1)	
14c	[1]105	[2]106	[1]106	---	106	(1)	(2,5)	
15a	[1]137	[4]132	---	---	131	(1)	(4,5)	Although evaluated with both brakes in and brakes out only by pilot B, pilots A and C believe that same approach speeds would apply to both configurations; hence, only one average approach speed presented for both configurations.
15b	---	[4]132	[1]125	---				
16a	[1]161	[1]149	[1]160	---	157	(1)	(3,5)	
16b	[1]149	[1]138	[1]149	[2]142	145	(1)	(3,4,5)	ΔT/W marginal
16c	[1]135	[1]130	[1]137	[1]133	134	(1)	(5,4)	Same as configuration 16b.

[1]Ability to control altitude or arrest rate of sink.
[2]Proximity to stall or other instability.
[3]Lateral-directional stability or control characteristics.
[4]Longitudinal control.
[5]Visibility from cockpit.



(a) FJ-3 airplane.

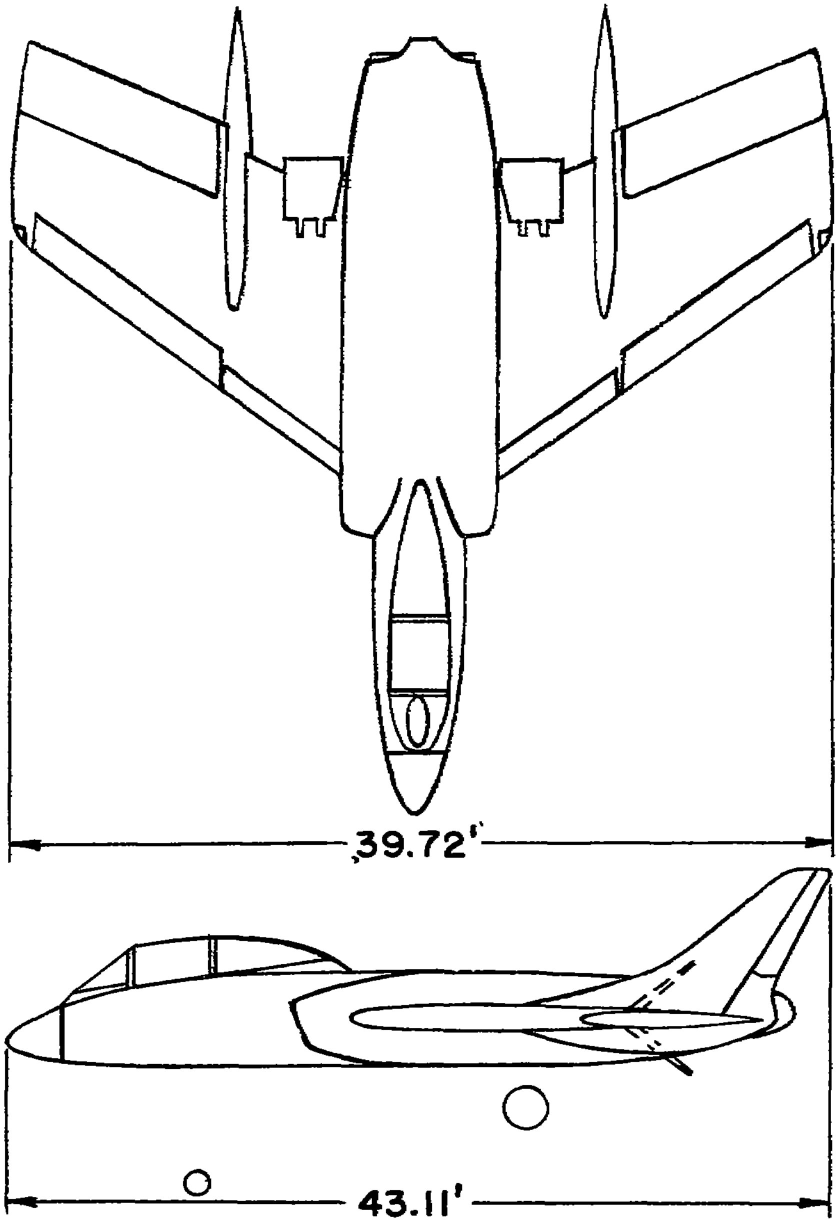
Figure 1.- Two-view drawing of the test airplanes.



(b) F4D airplane.

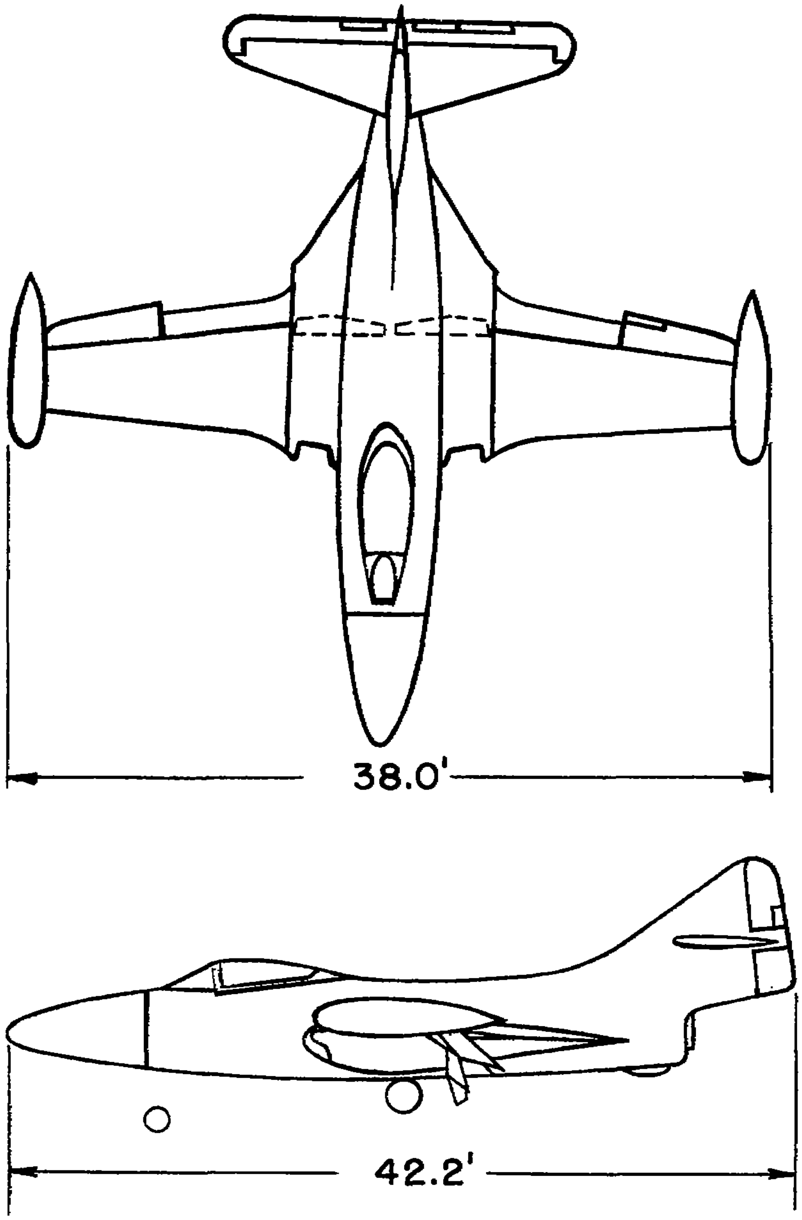
Figure 1.- Continued.

[redacted]



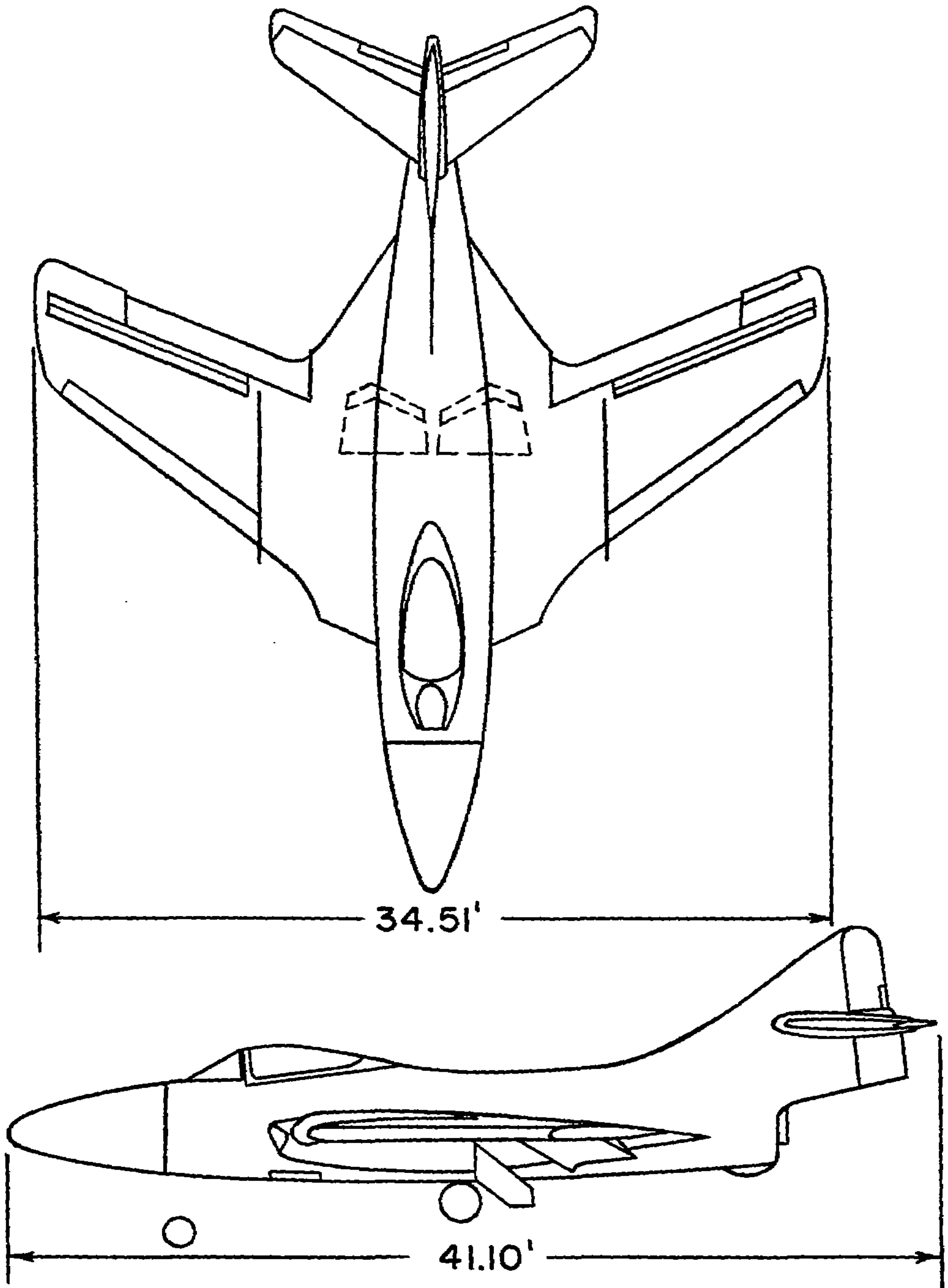
(c) F7U-3 airplane.

Figure 1.- Continued.



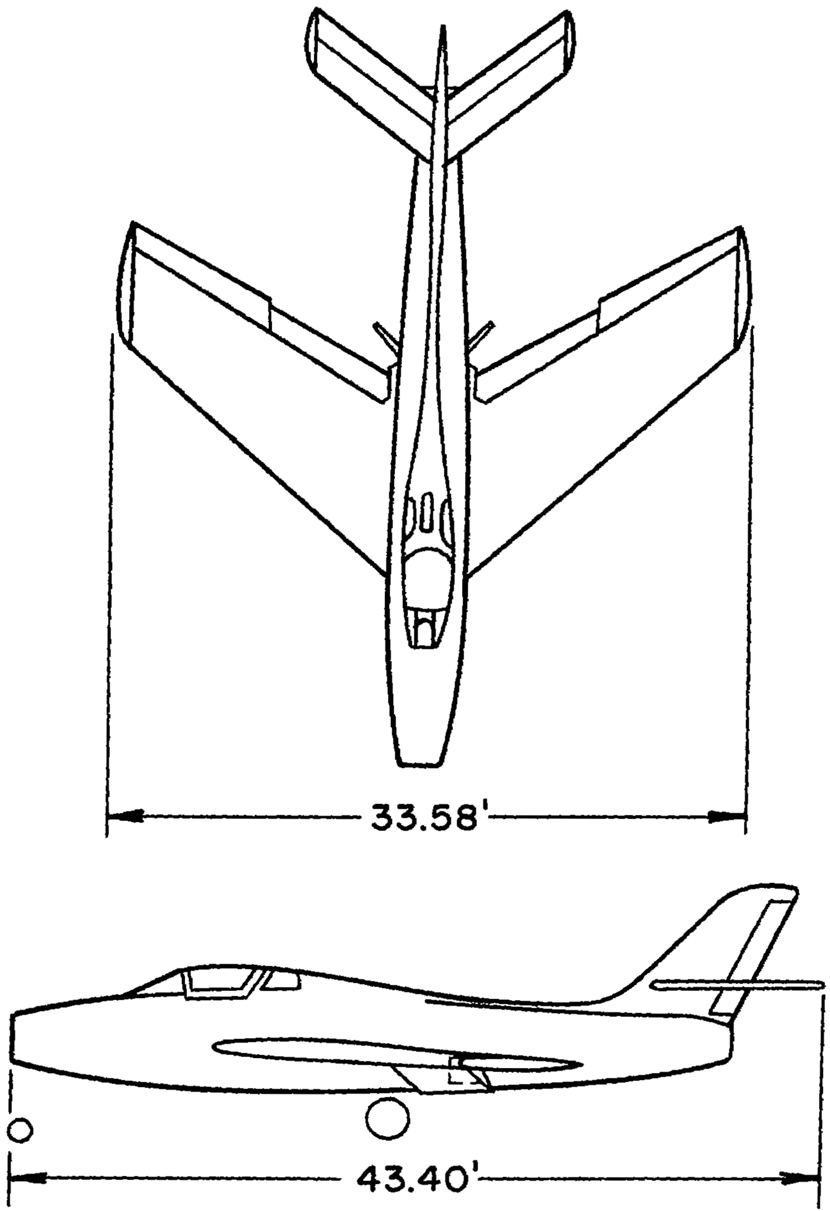
(d) F9F-4 airplane.

Figure 1.- Continued.



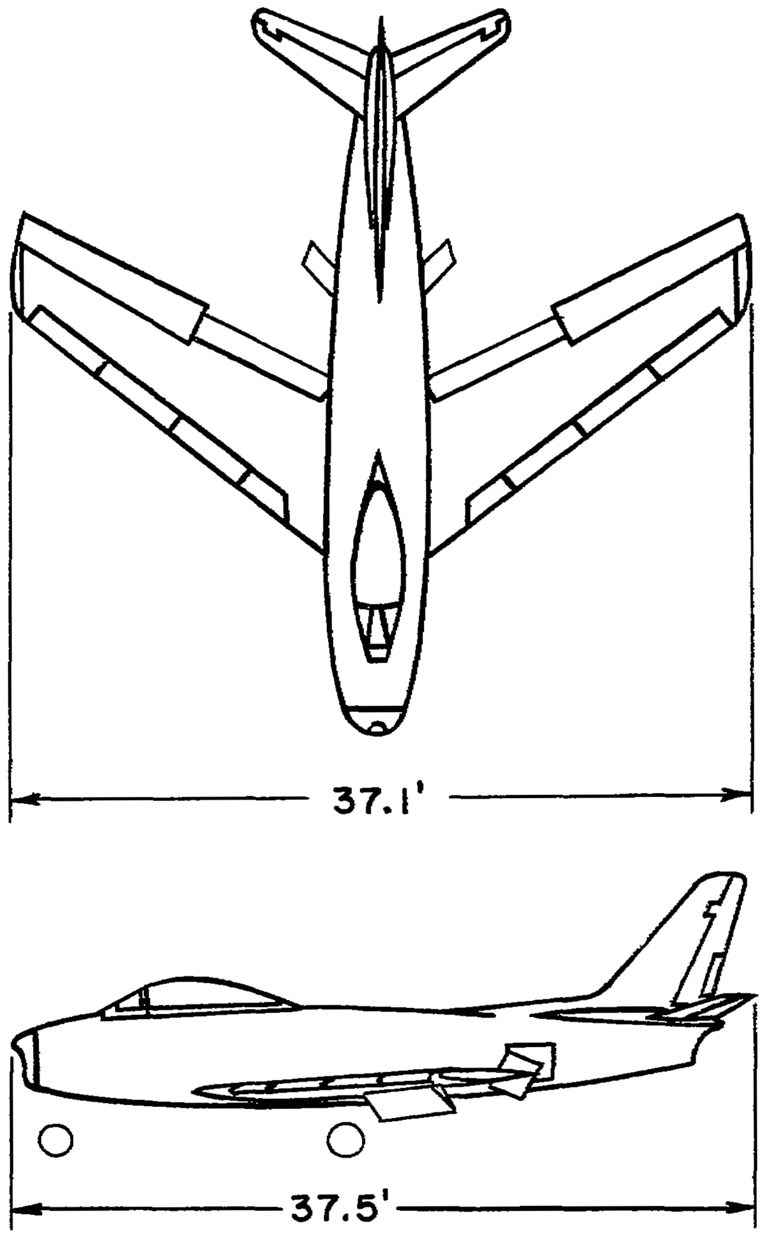
(e) F9F-6 airplane.

Figure 1.- Continued.



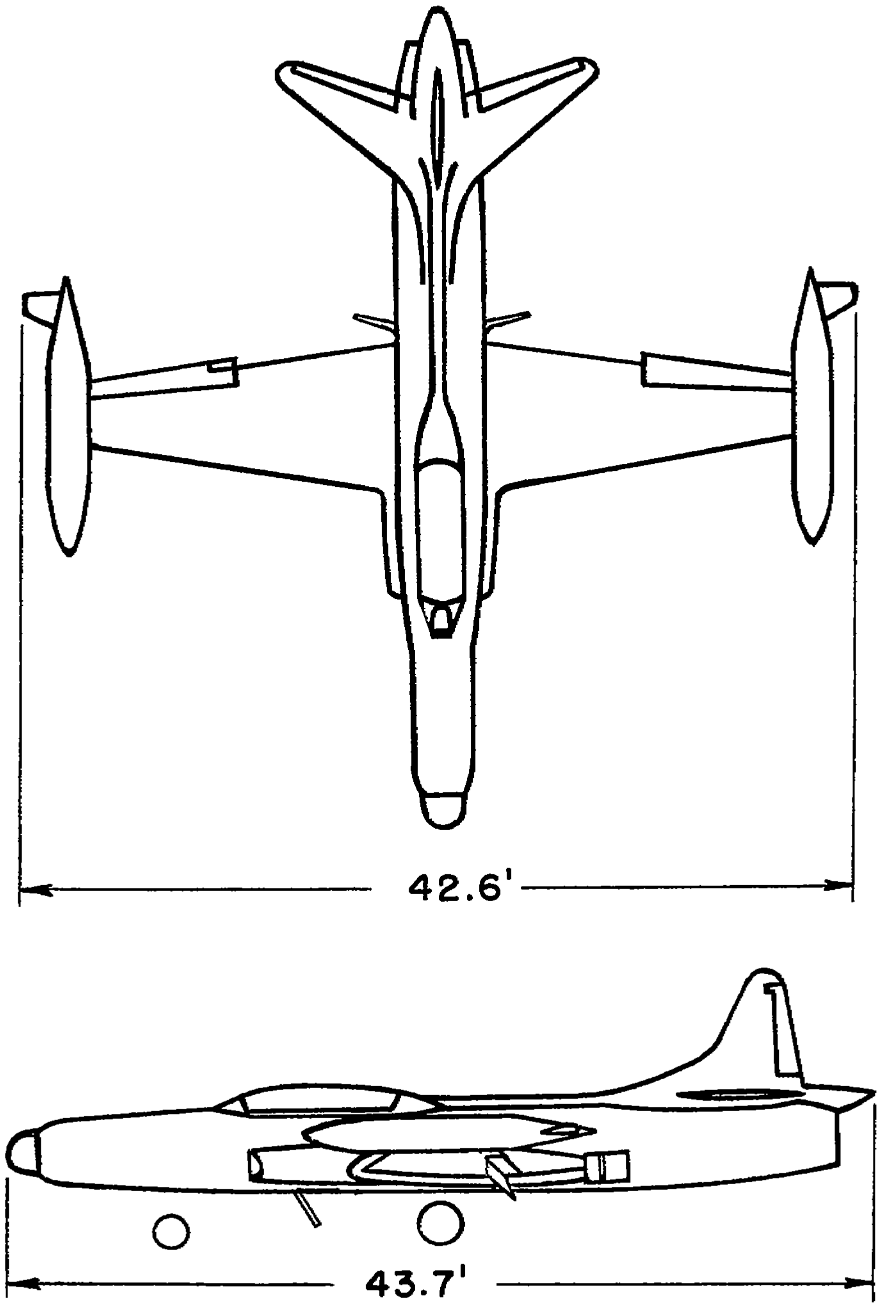
(f) F-84F airplane.

Figure 1.- Continued.



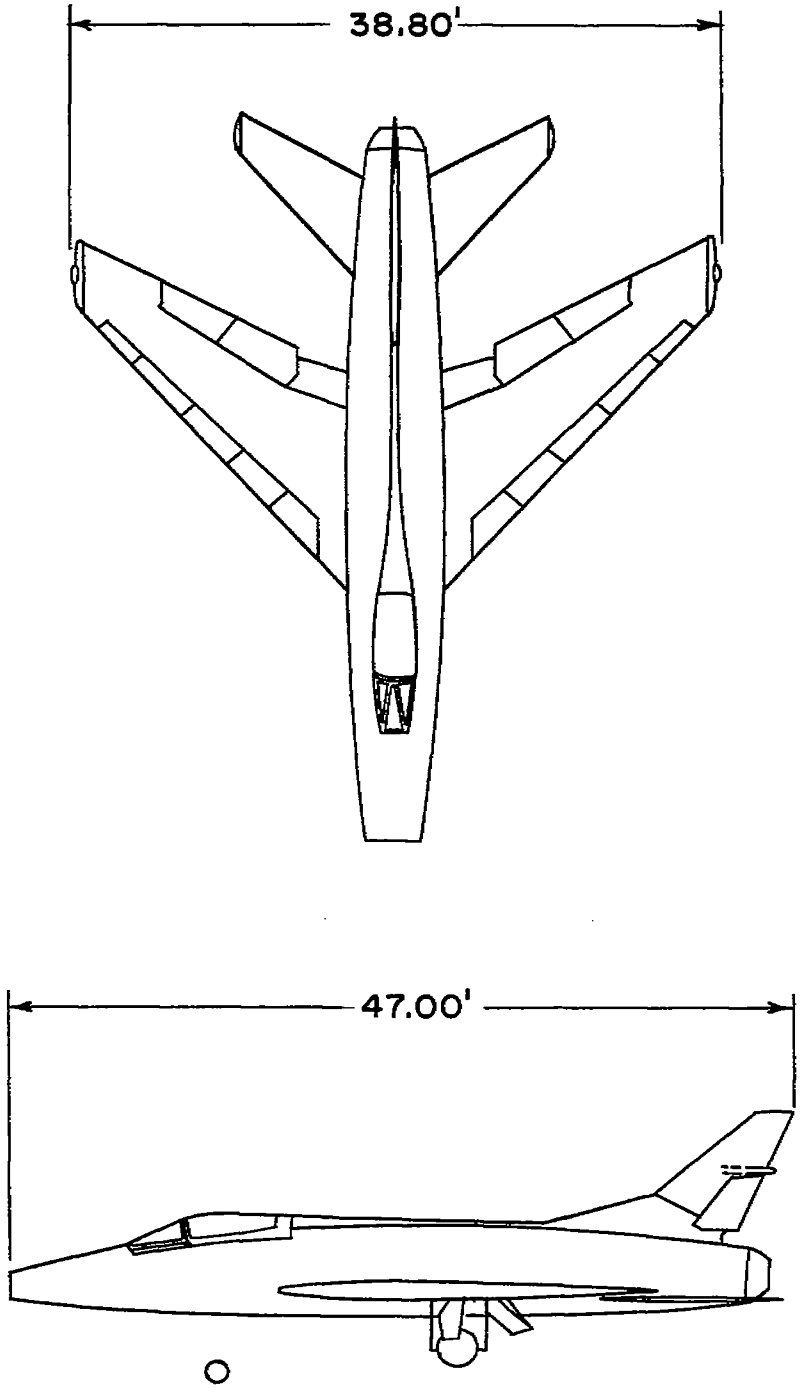
(g) F-86A and F-86F airplanes.

Figure 1.- Continued.



(h) F-94C airplane.

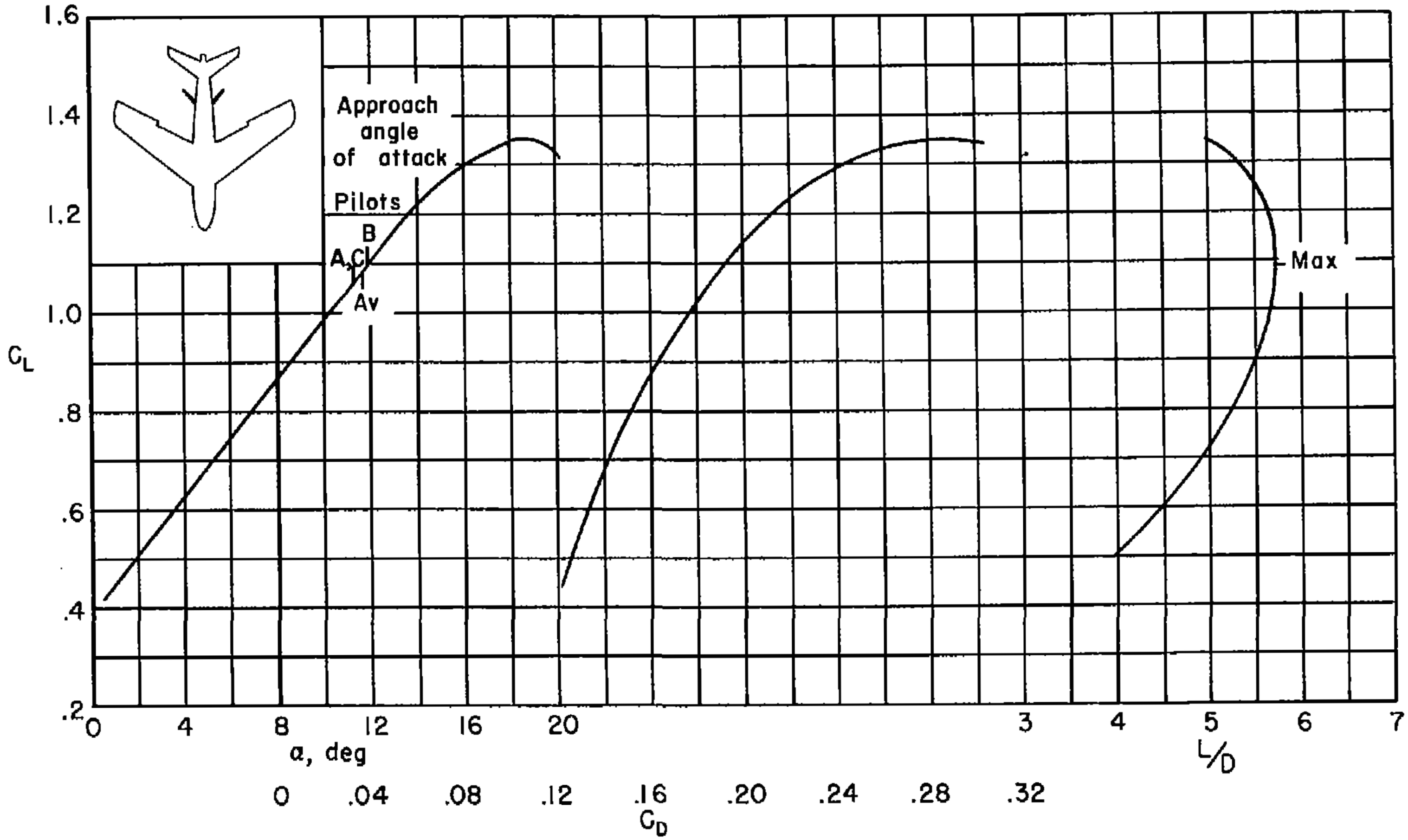
Figure 1.- Continued.



(i) F-100A airplane (flap added).

Figure 1.- Concluded.

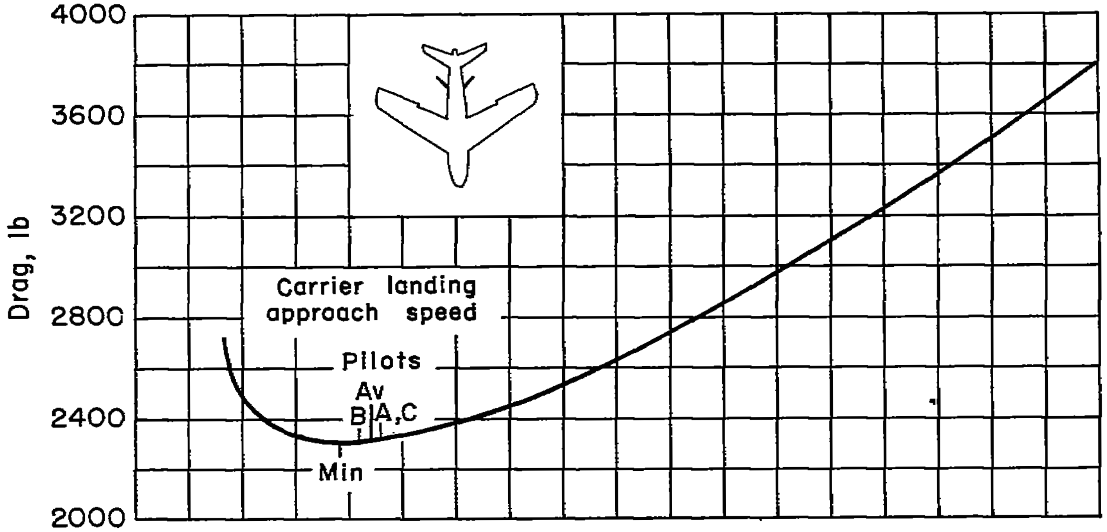
[redacted]



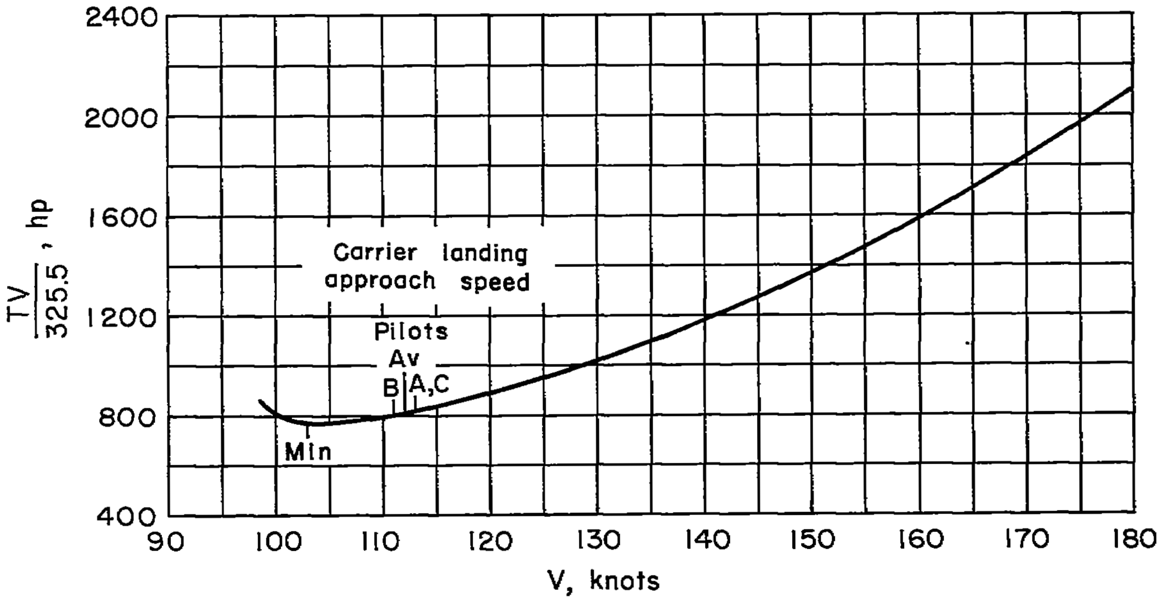
[redacted]

(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 2.- Aerodynamic characteristics of the FJ-3 airplane; slotted flap, $\delta_f = 45^\circ$, leading-edge slats (config. 1).

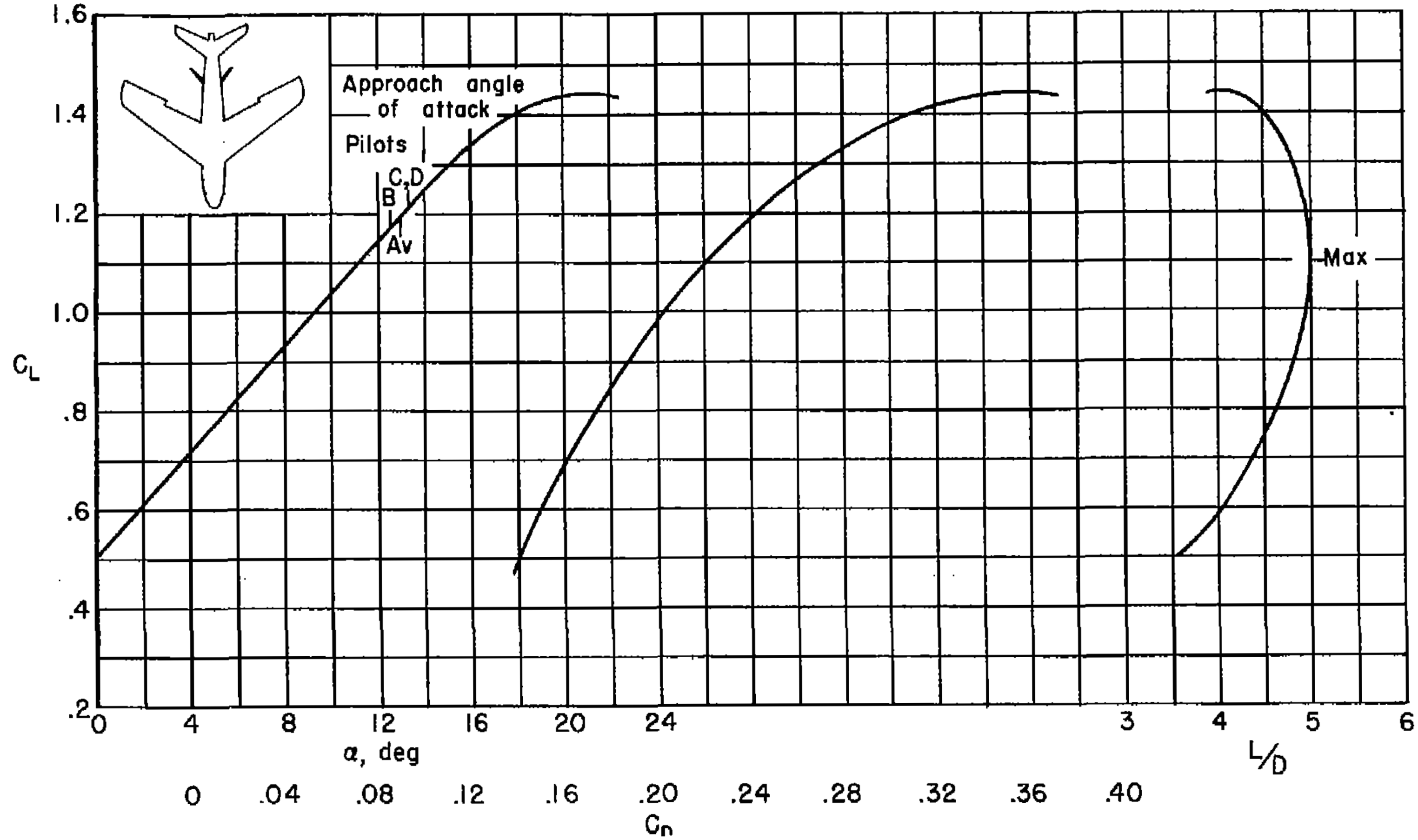


(b) Variation of airplane drag with velocity.



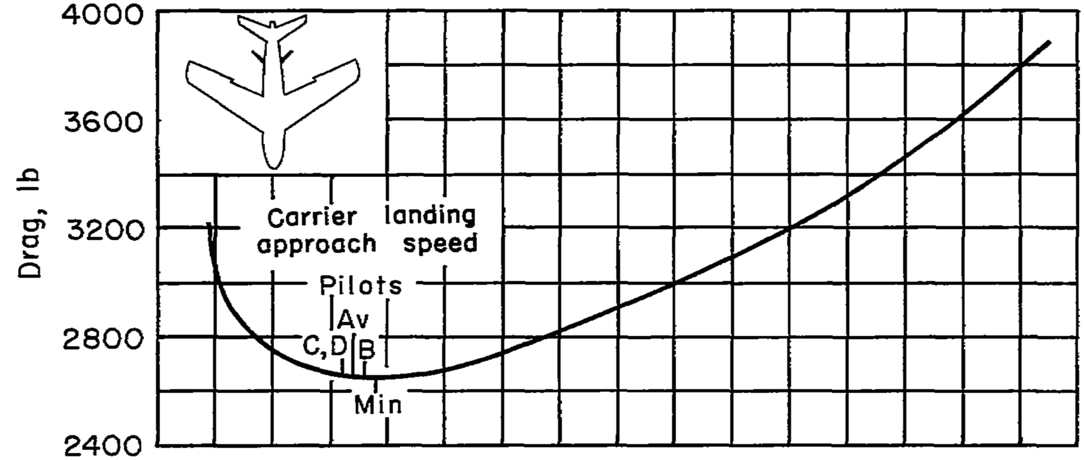
(c) Variation of horsepower required for level flight with velocity.

Figure 2.- Concluded.

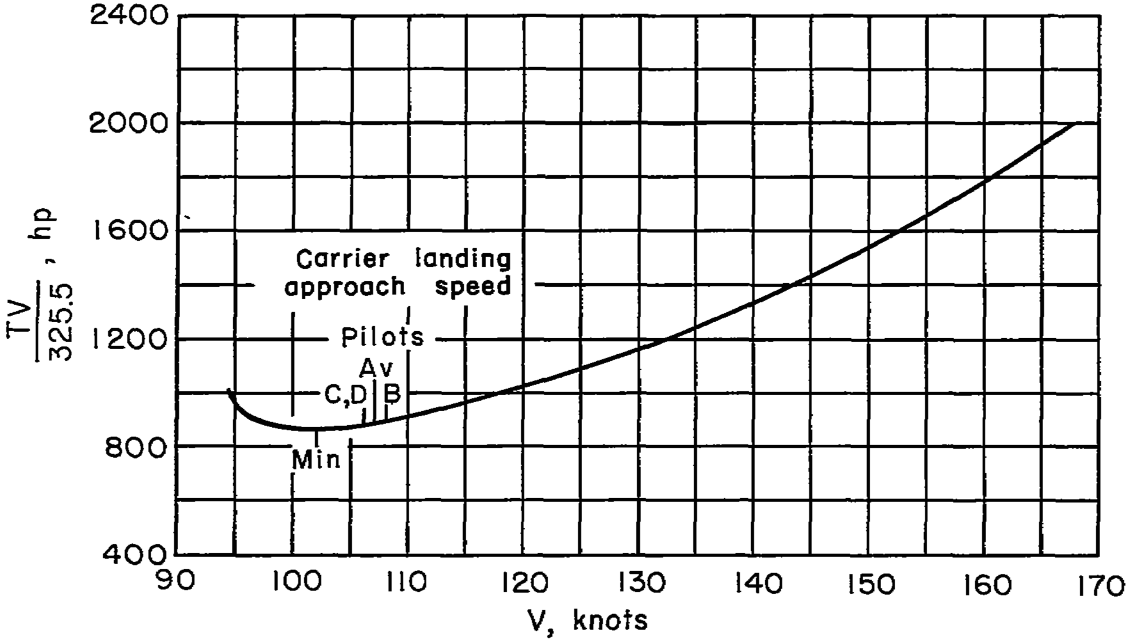


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 3.- Aerodynamic characteristics of the FJ-3 airplane; plain flap, $\delta_f = 55^\circ$, leading-edge slats, suction-flap BLC (config. 2a).



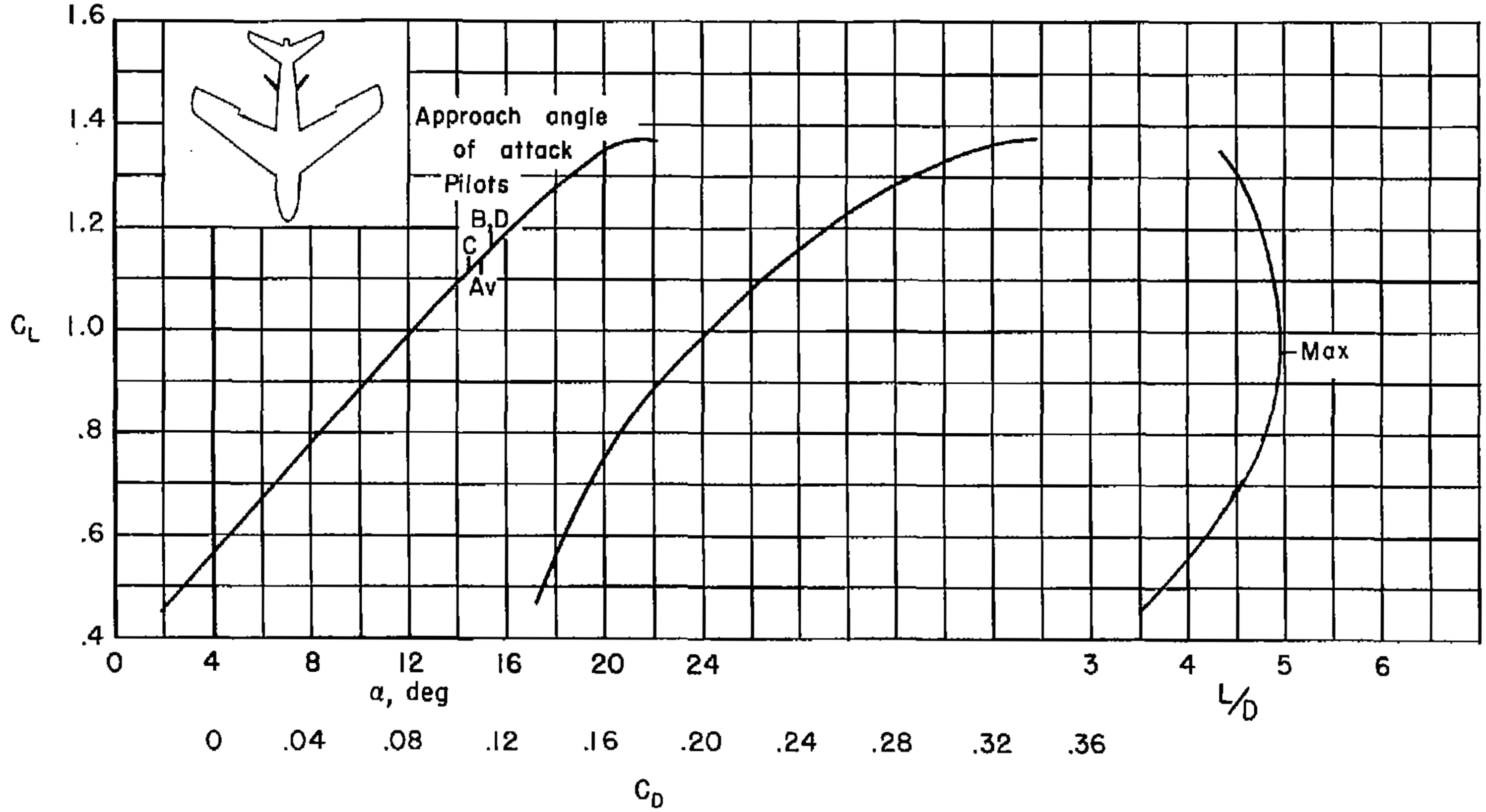
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

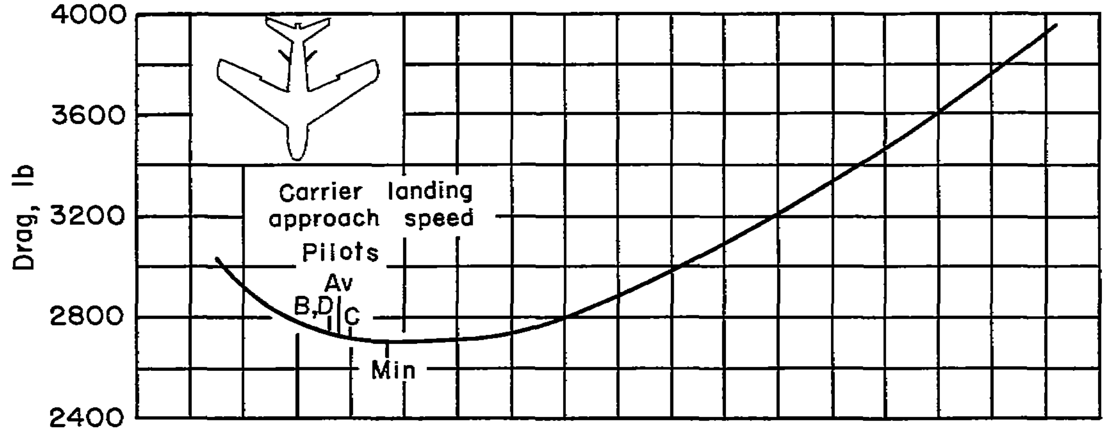
Figure 3.- Concluded.

[redacted]

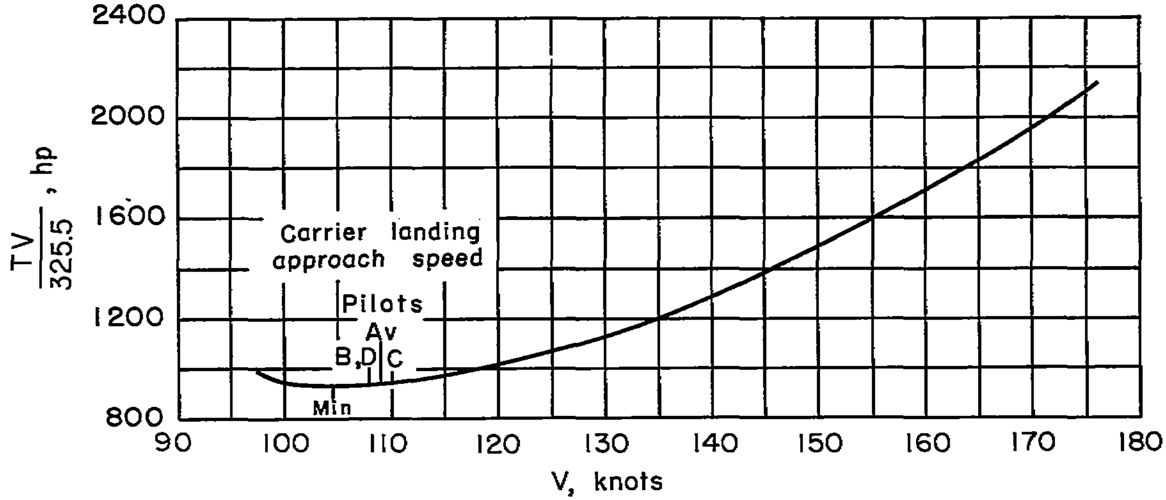


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 4.- Aerodynamic characteristics of the FJ-3 airplane; plain flap, $\delta_f = 55^\circ$, leading-edge slats (config. 2b).



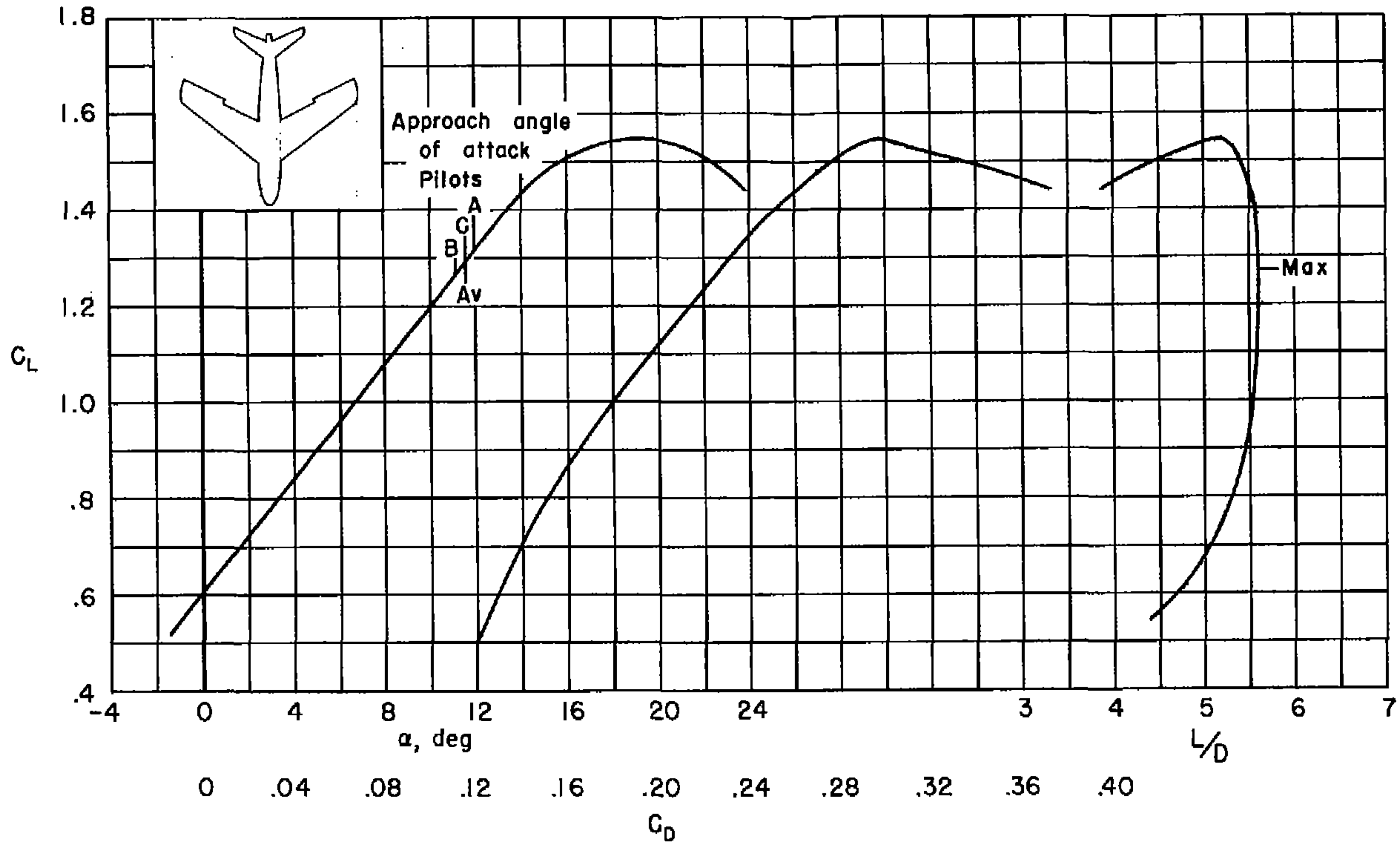
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 4.- Concluded.

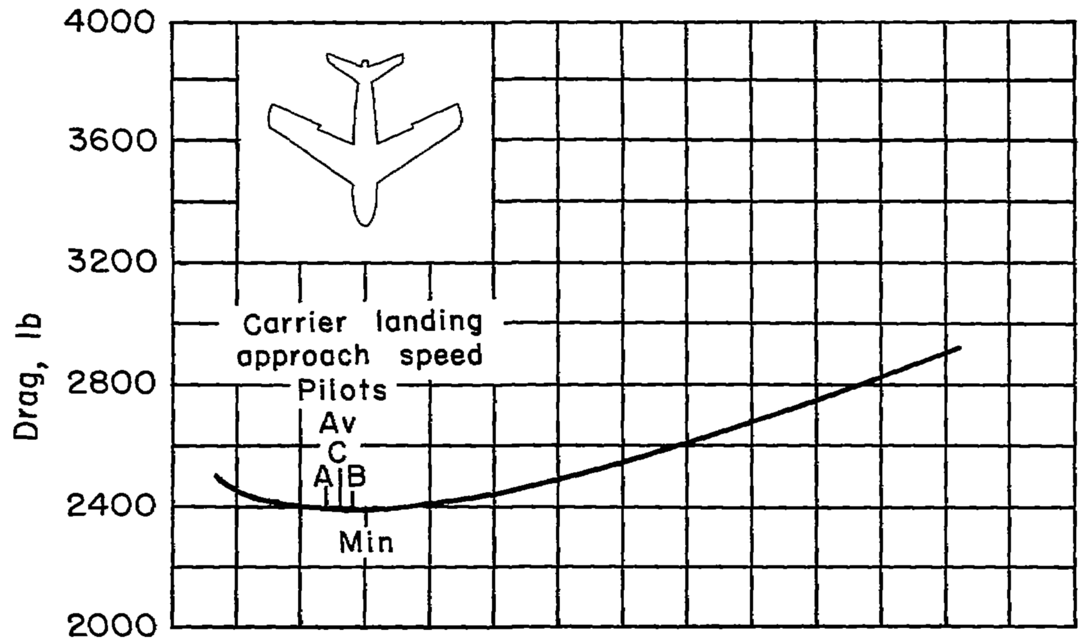
[redacted]



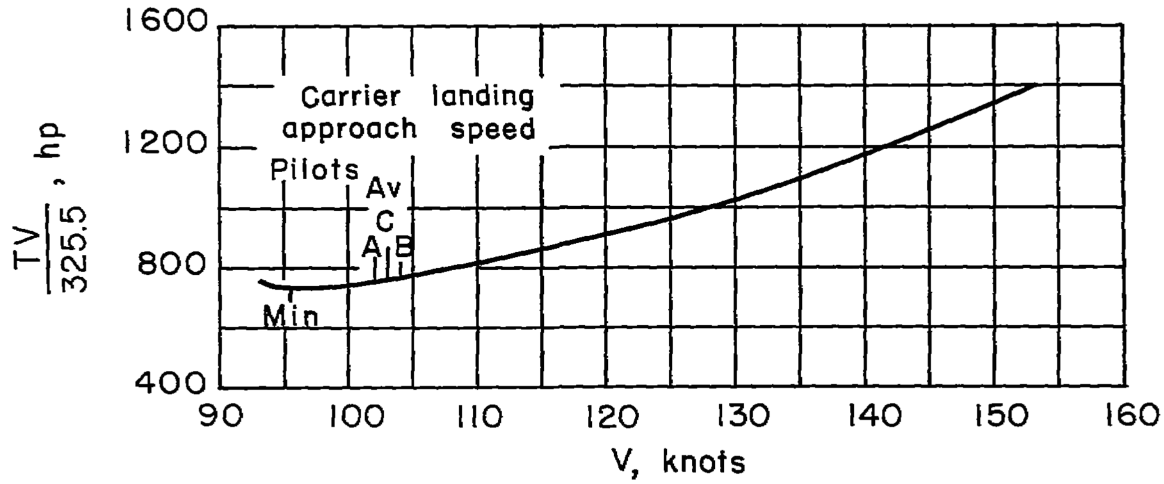
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 5.- Aerodynamic characteristics of the FJ-3 airplane; plain flap, $\delta_f = 55^\circ$, leading-edge slats, blowing-flap BLC (config. 2c).

[redacted]

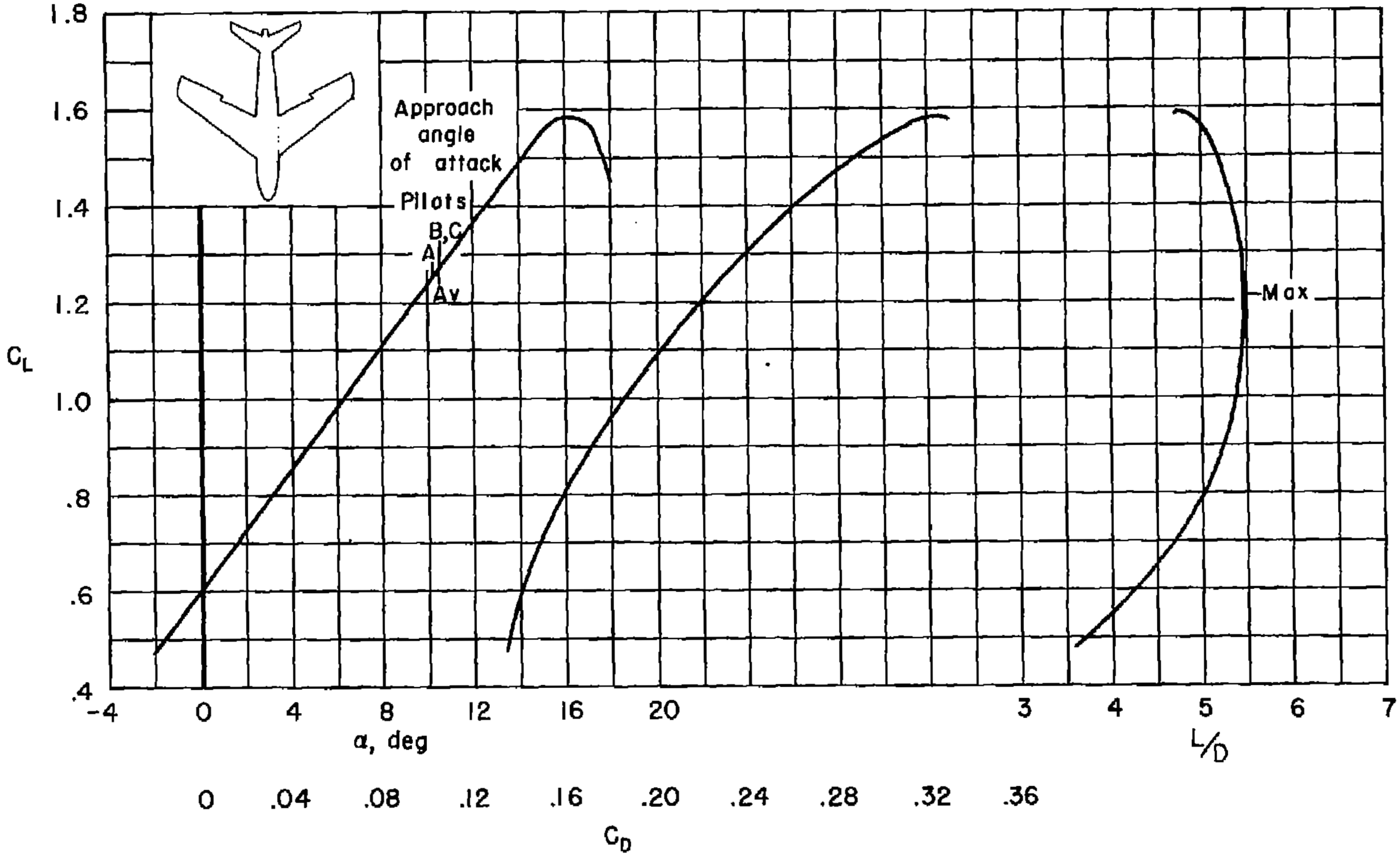


(b) Variation of airplane drag with velocity.



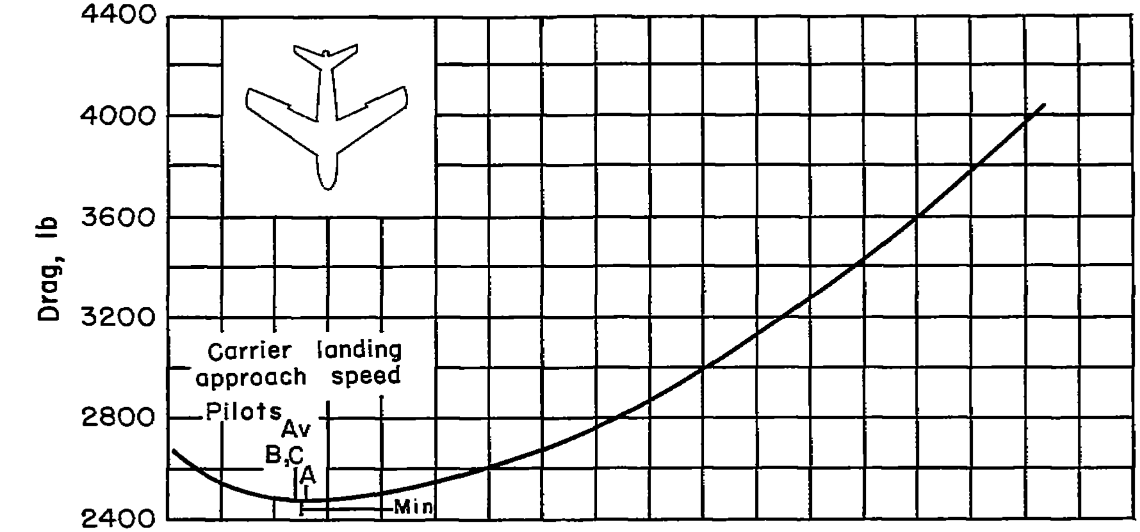
(c) Variation of horsepower required for level flight with velocity.

Figure 5.- Concluded.

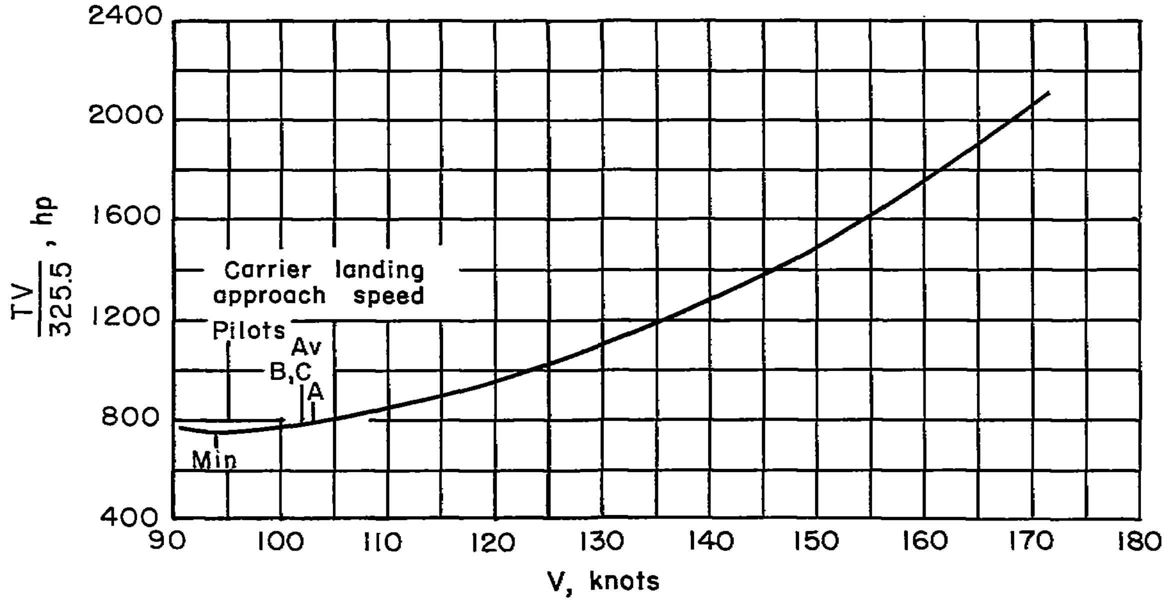


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 6.- Aerodynamic characteristics of the FJ-3 airplane; plain flap, $\delta_f = 55^\circ$, leading-edge camber, fence, blowing-flap BLC (config. 3a).

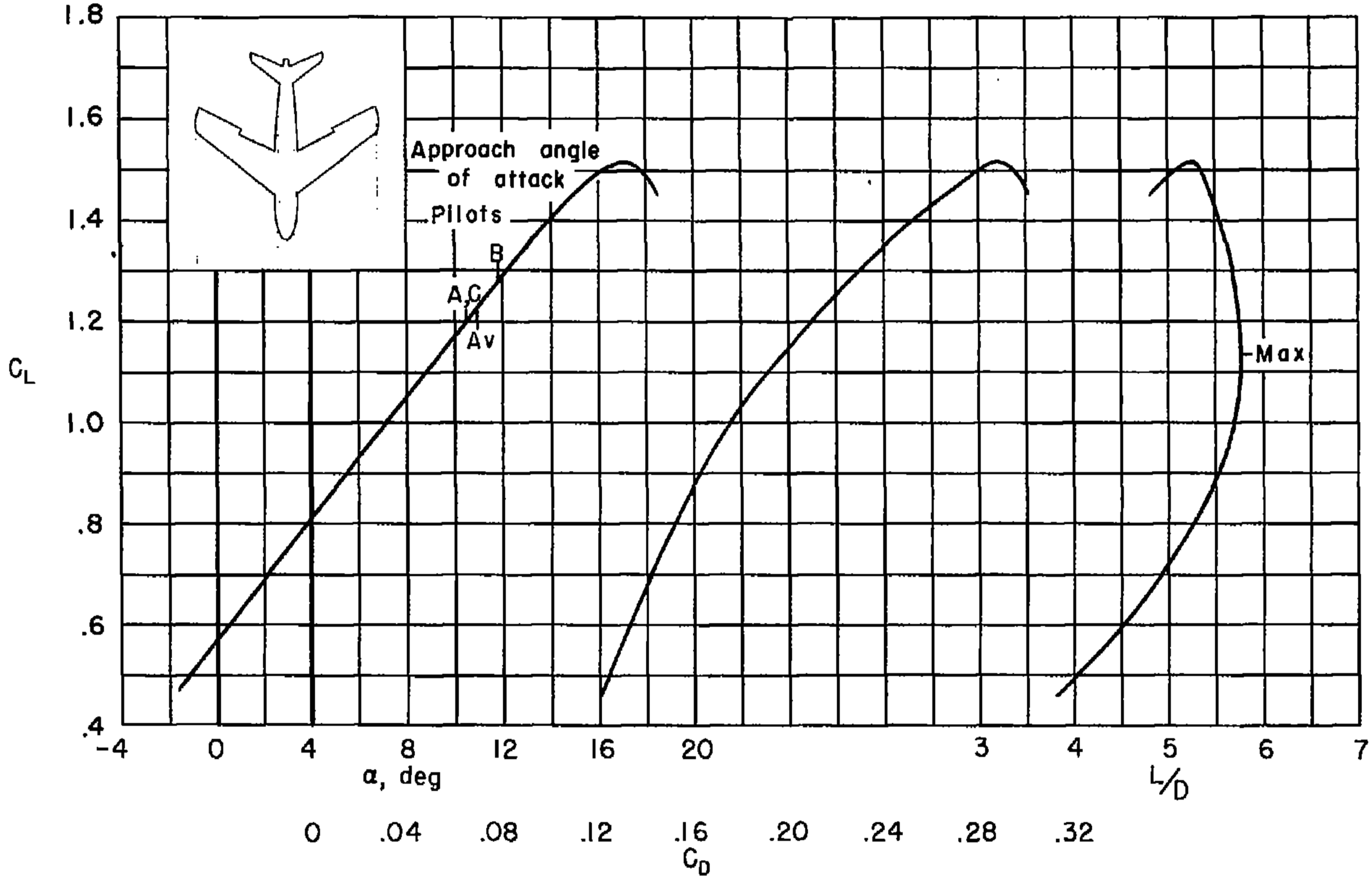


(b) Variation of airplane drag with velocity.



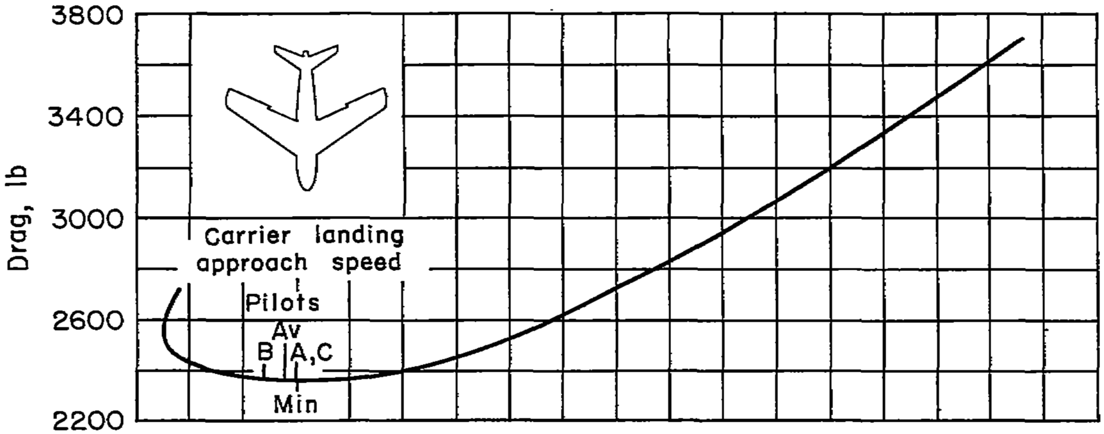
(c) Variation of horsepower required for level flight with velocity.

Figure 6.- Concluded.

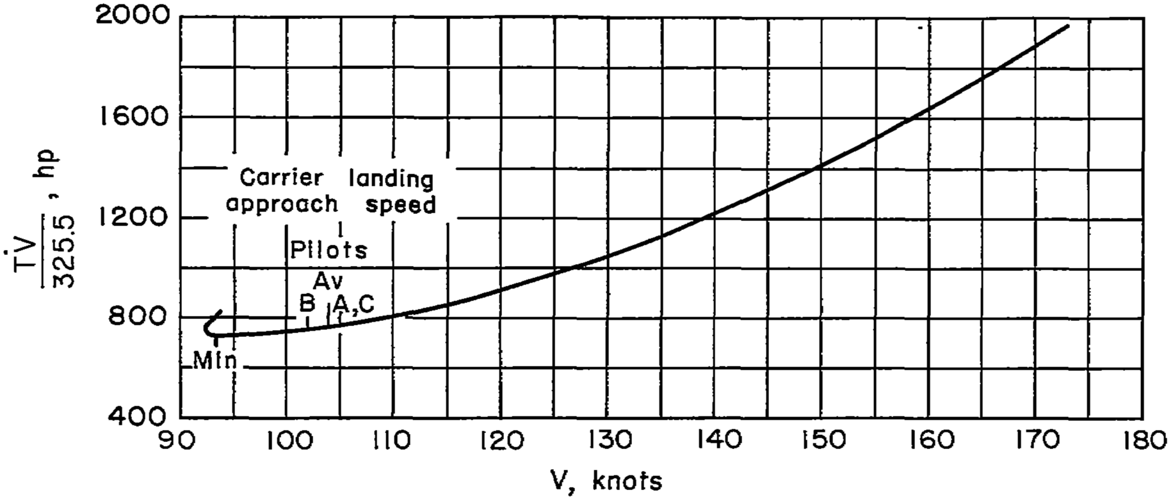


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 7.- Aerodynamic characteristics of the FJ-3 airplane; plain flap, $\delta_f = 55^\circ$, leading-edge camber, fence, blowing-flap BLC (config. 3b).

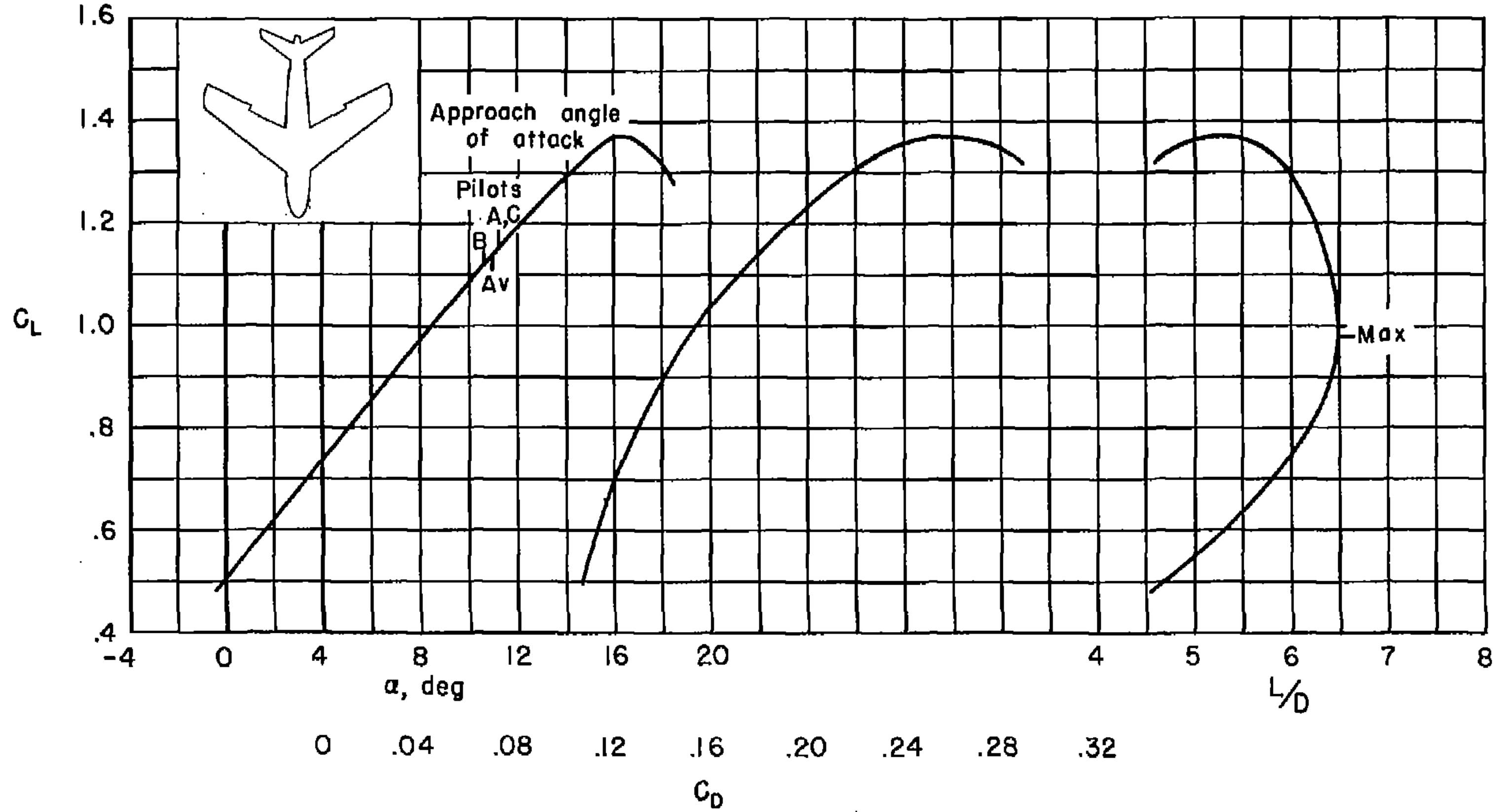


(b) Variation of airplane drag with velocity.



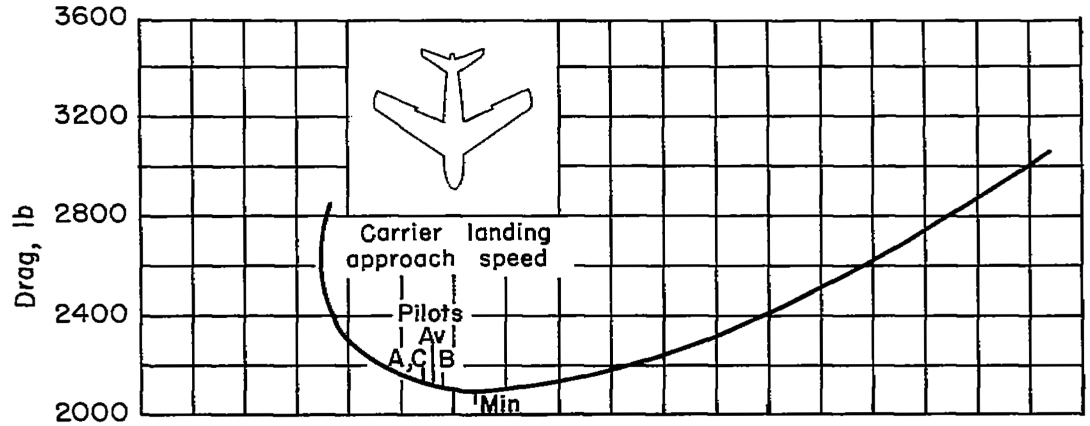
(c) Variation of horsepower required for level flight with velocity.

Figure 7.- Concluded.

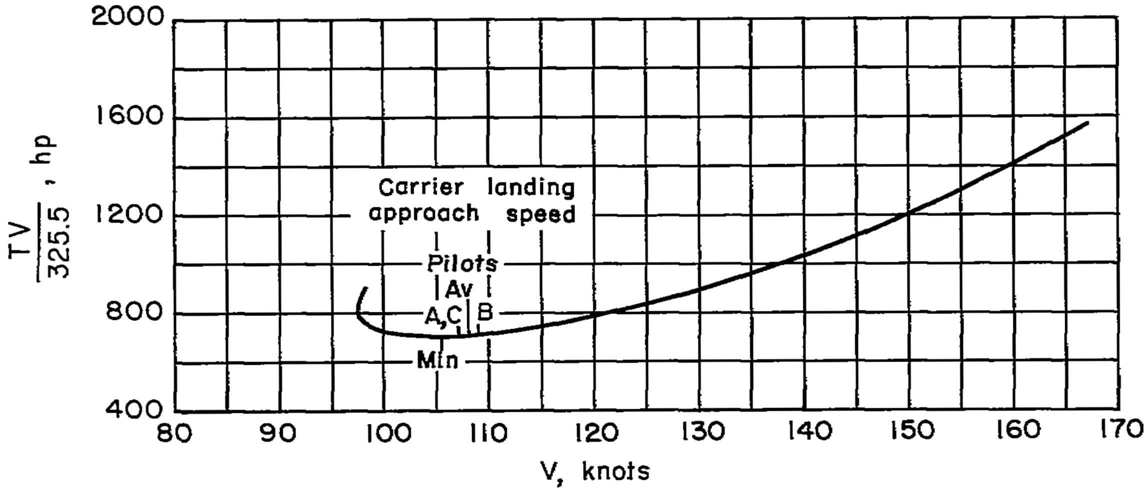


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 8.- Aerodynamic characteristics of the FJ-3 airplane; plain flap, $\delta_f = 55^\circ$, leading-edge camber, fence, suction-flap BLC (config. 3c).



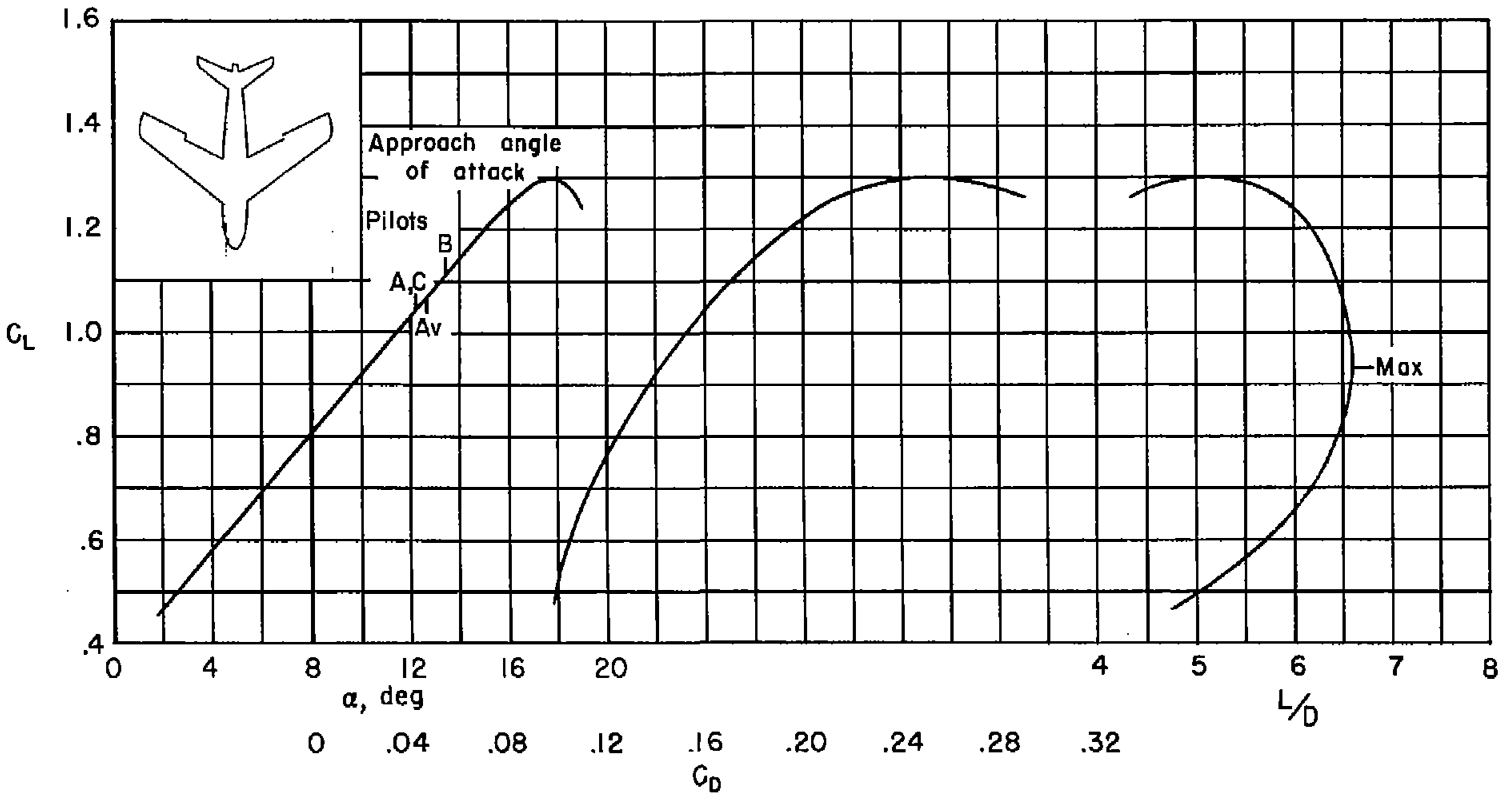
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 8.- Concluded.

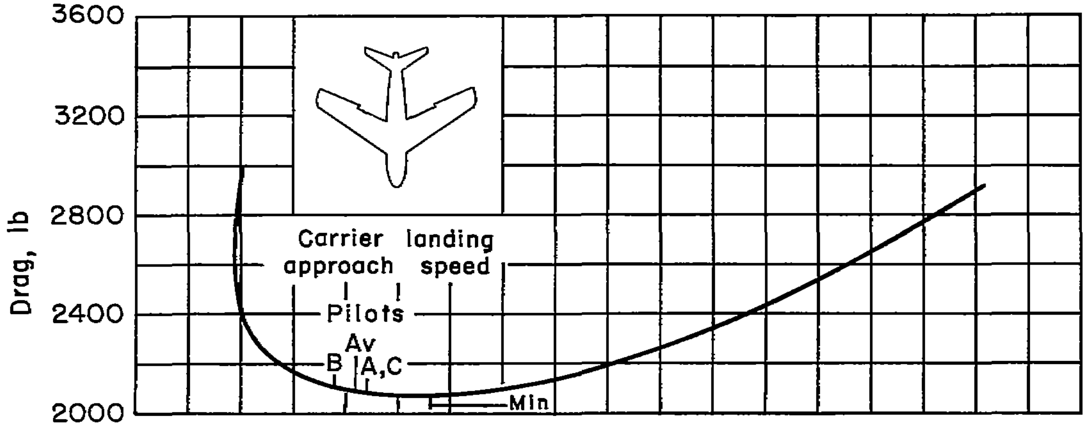
[redacted]



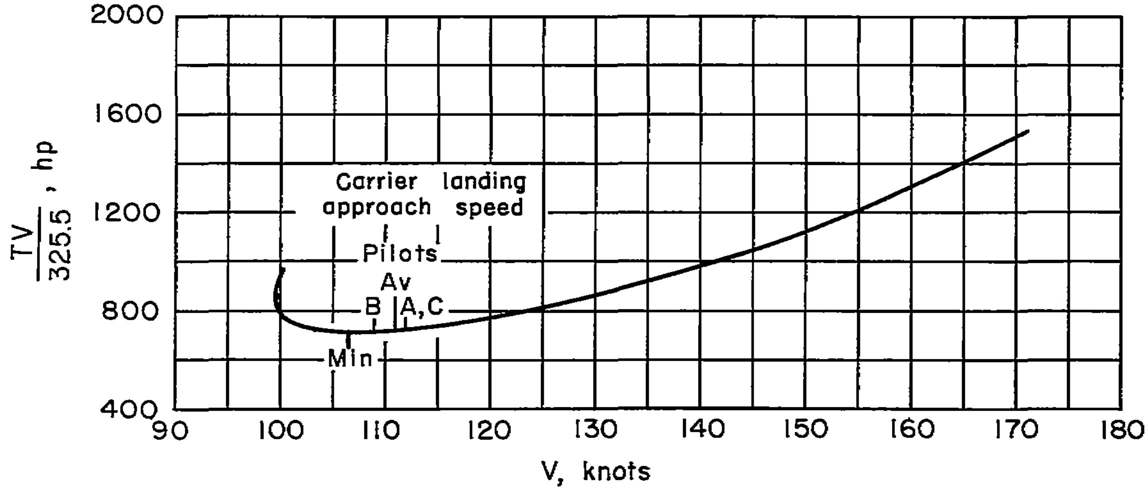
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 9.- Aerodynamic characteristics of the FJ-3 airplane; plain flap, $\delta_f = 55^{\circ}$, leading-edge camber, fence (config. 3d).

[redacted]

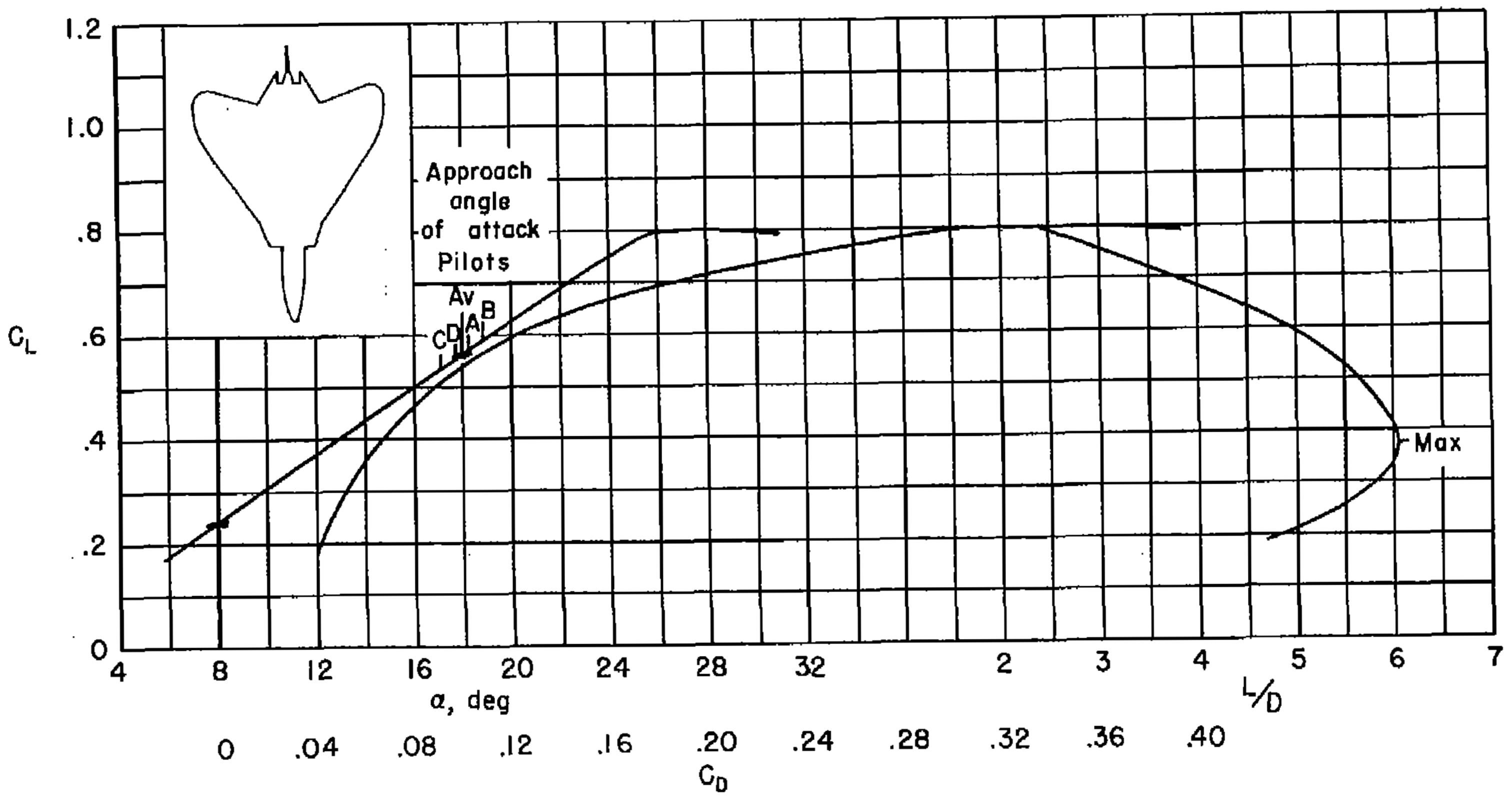


(b) Variation of airplane drag with velocity.



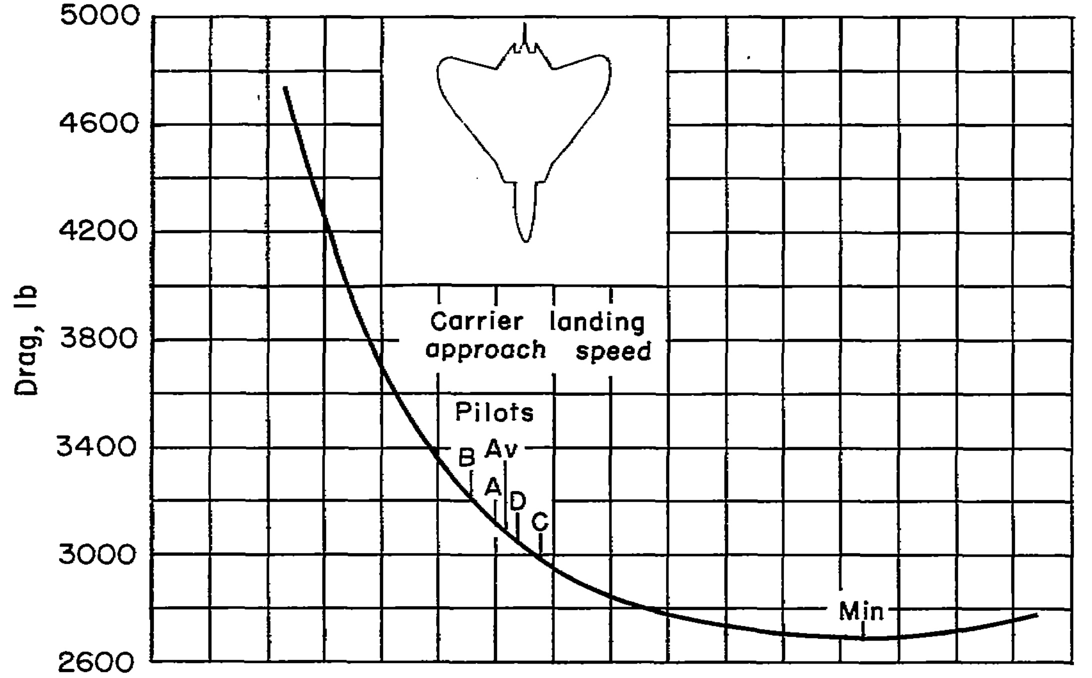
(c) Variation of horsepower required for level flight with velocity.

Figure 9.- Concluded.

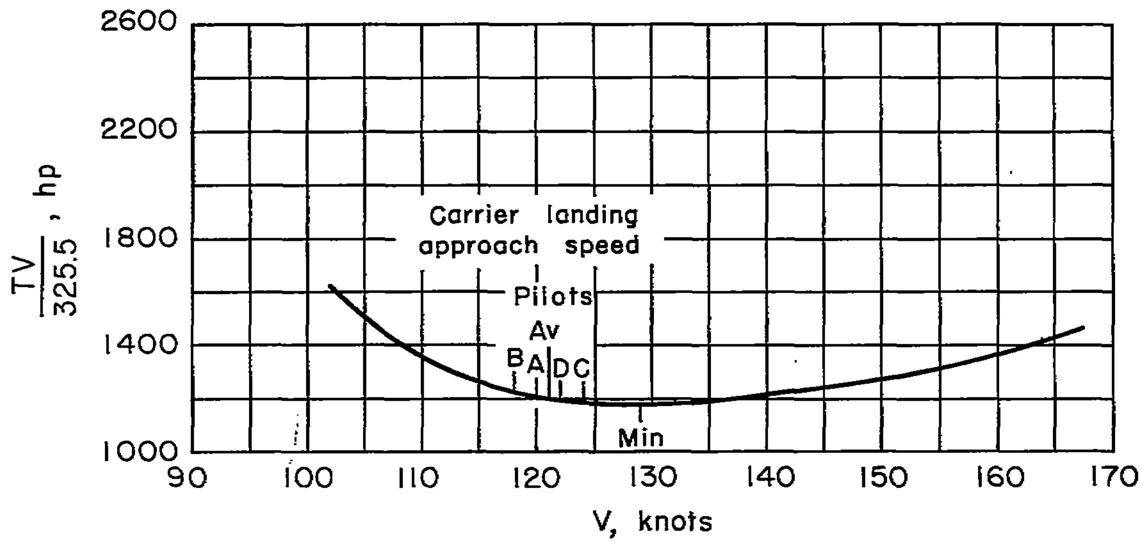


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 10.- Aerodynamic characteristics of the F4D airplane; leading-edge slats (config. 4a).

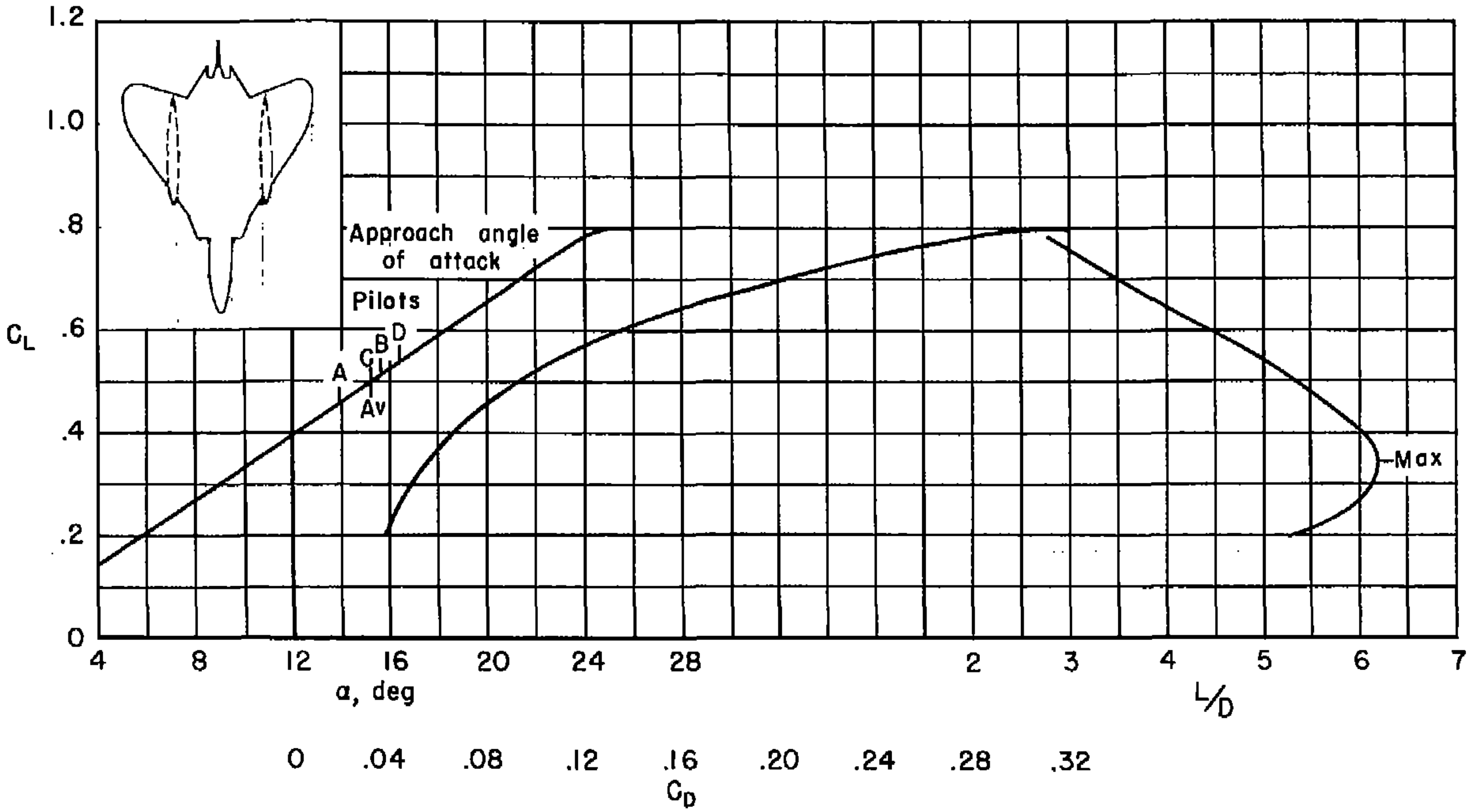


(b) Variation of airplane drag with velocity.



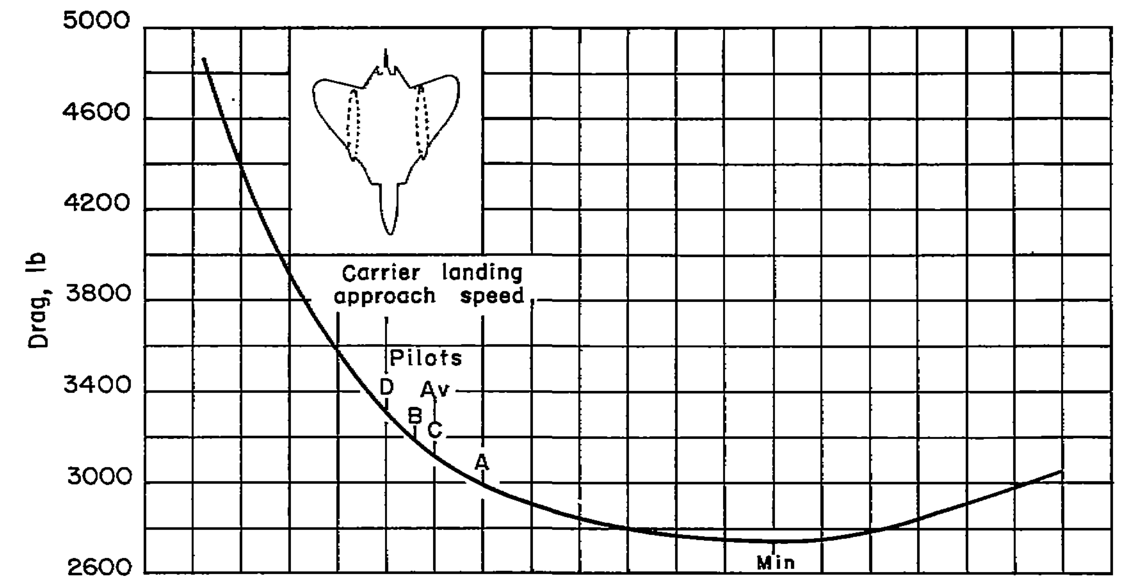
(c) Variation of horsepower required for level flight with velocity.

Figure 10.- Concluded.

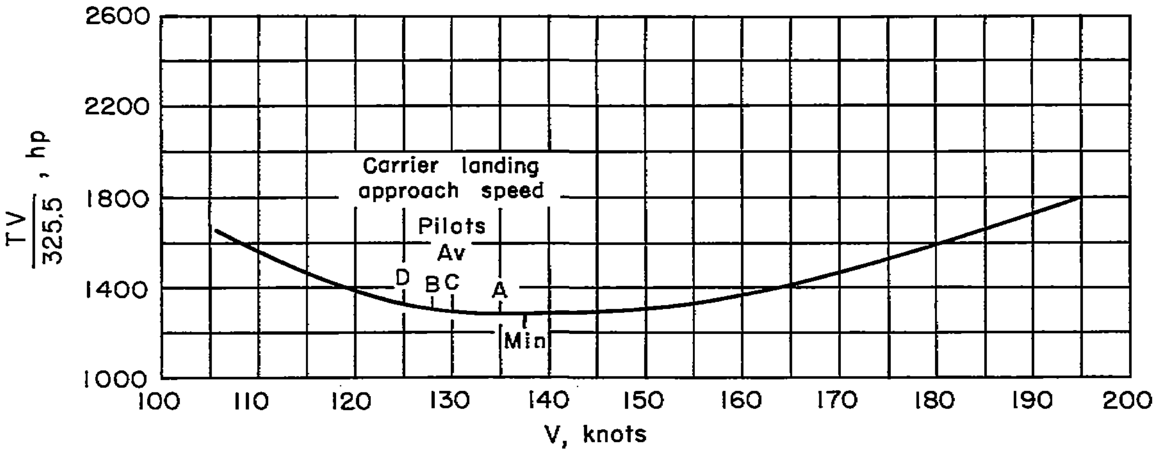


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 11.- Aerodynamic characteristics of the F4D airplane; leading-edge slats, tanks (config. 4b).



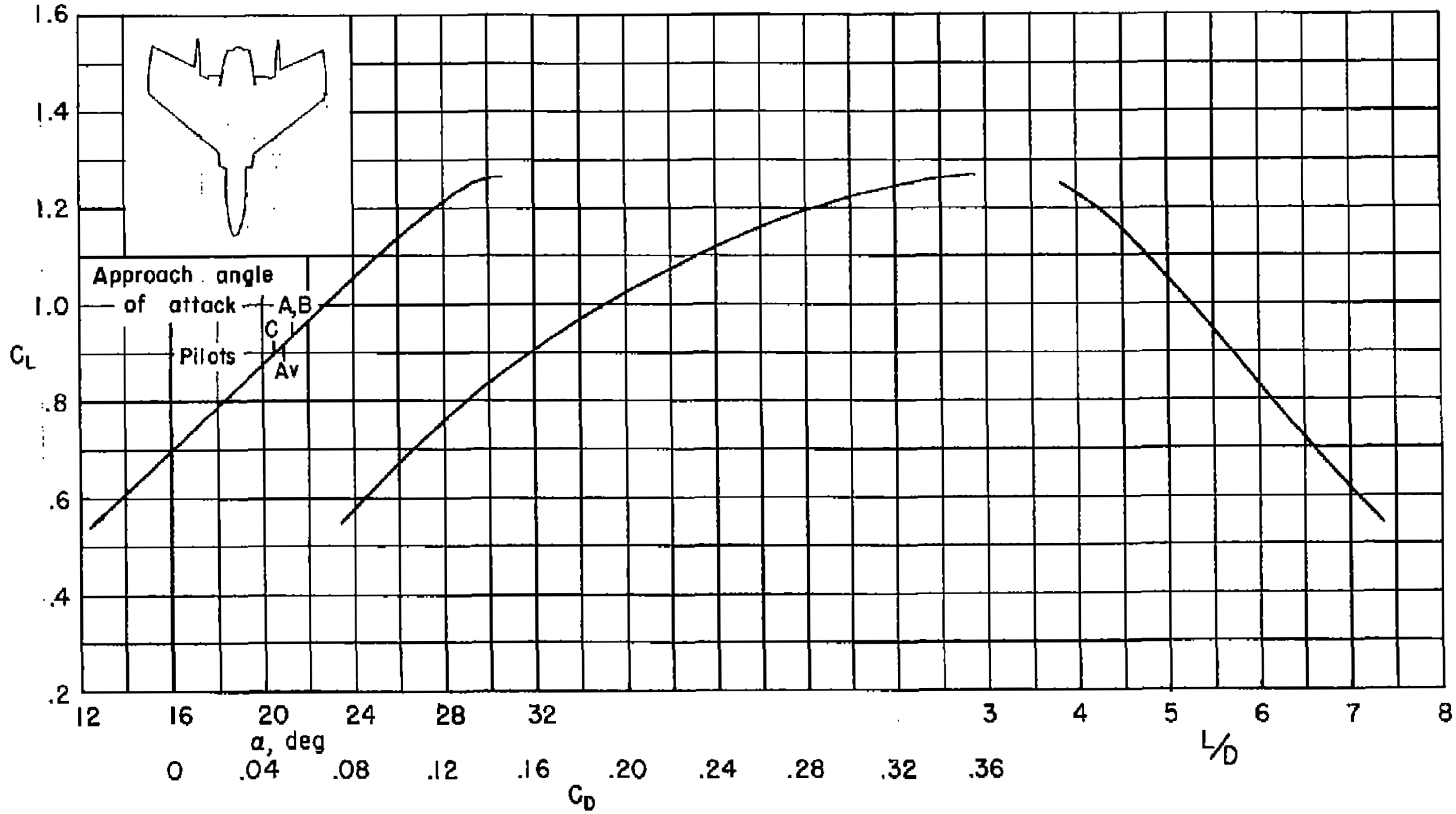
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 11.- Concluded.

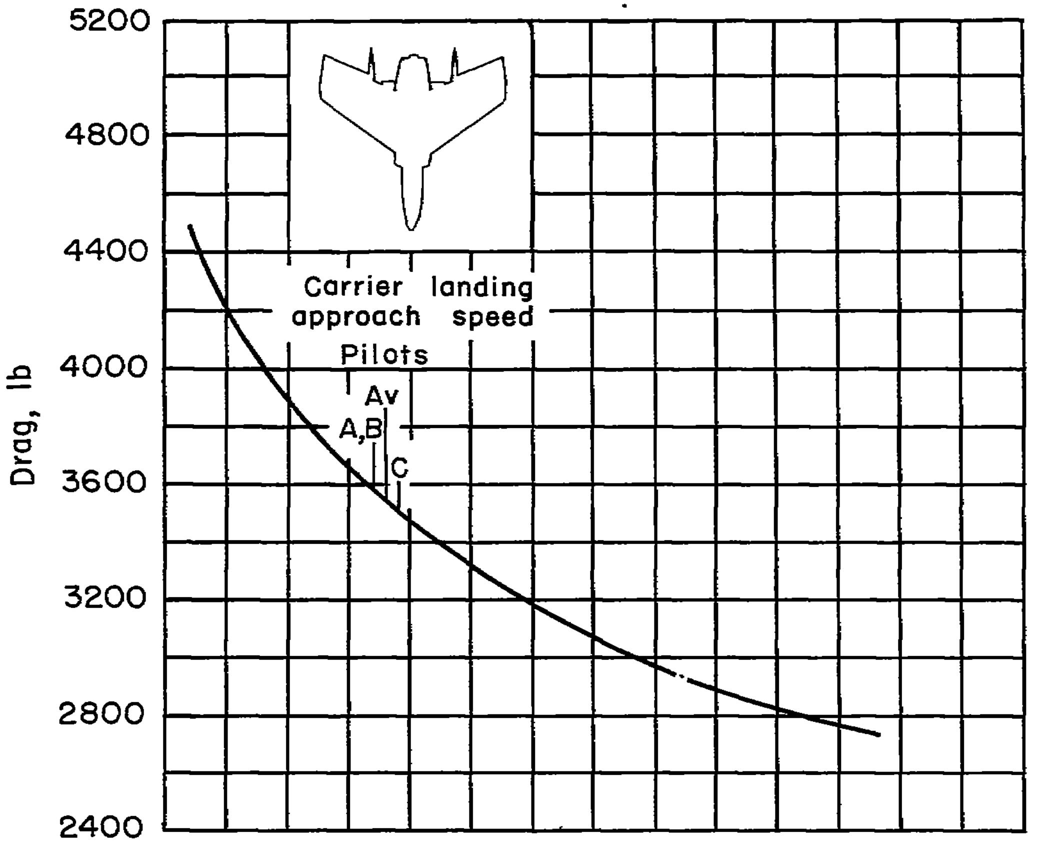
[redacted]



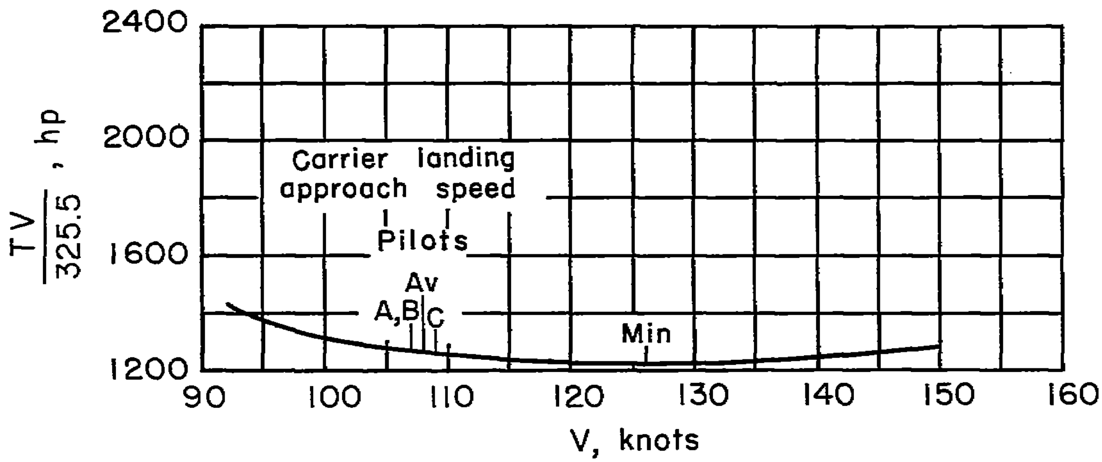
[redacted]

(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 12.- Aerodynamic characteristics of the F7U-3 airplane; leading-edge slats (config. 5a).



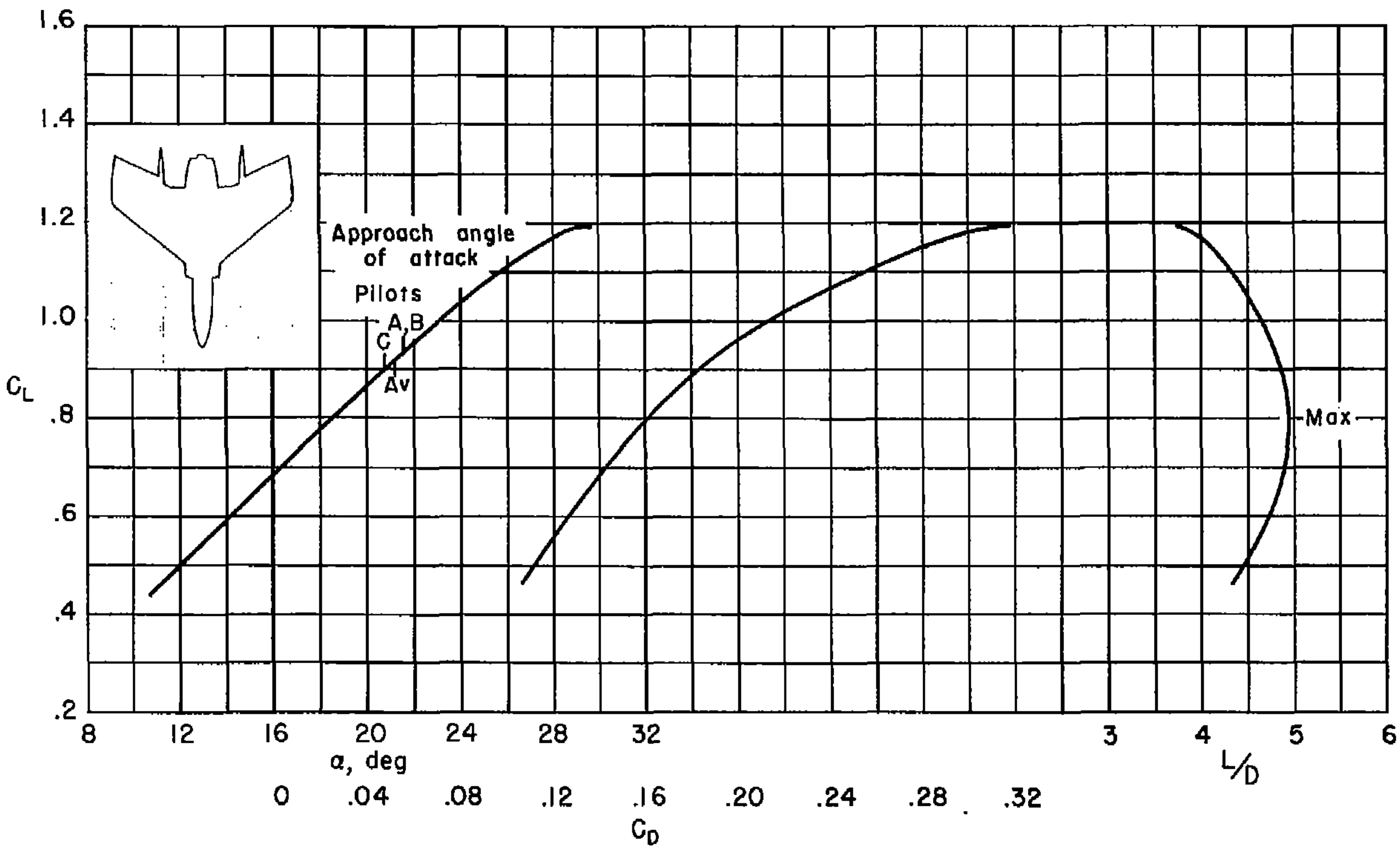
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 12.- Concluded.

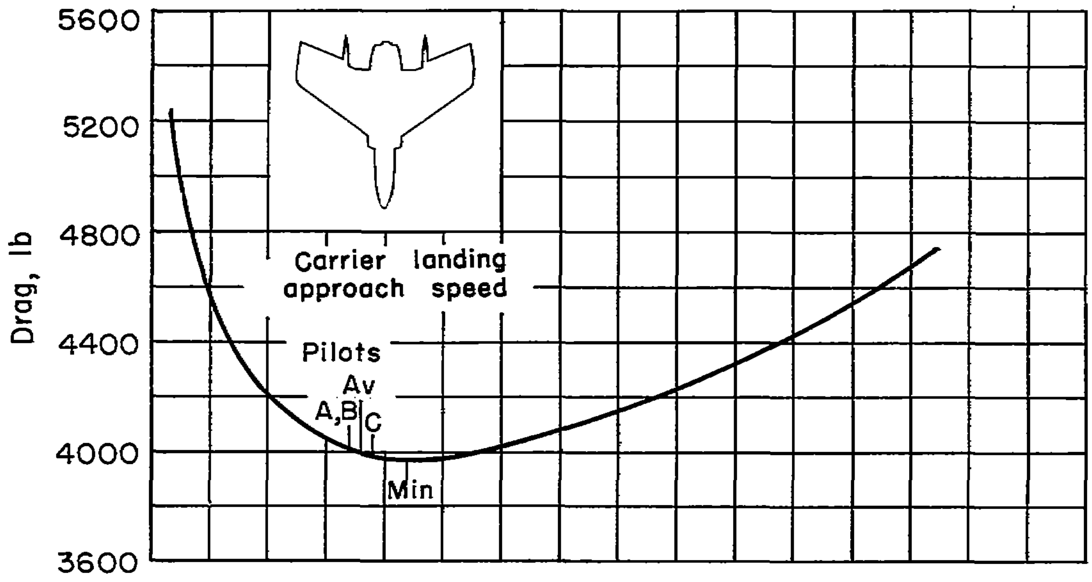
[redacted]



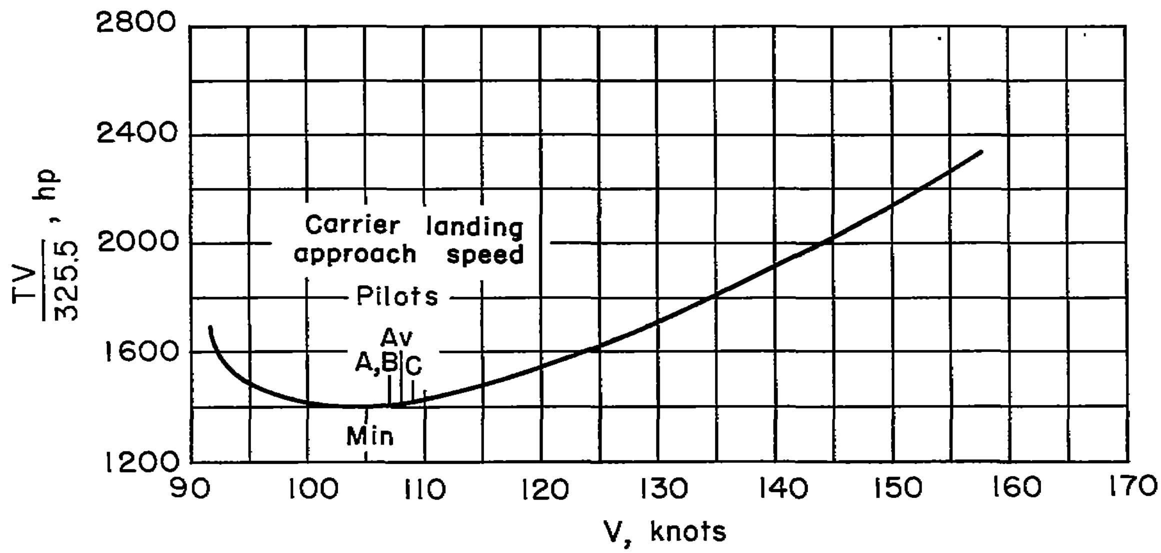
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 13.- Aerodynamic characteristics of the F7U-3 airplane; leading-edge slats, speed brakes (config. 5b).

[redacted]

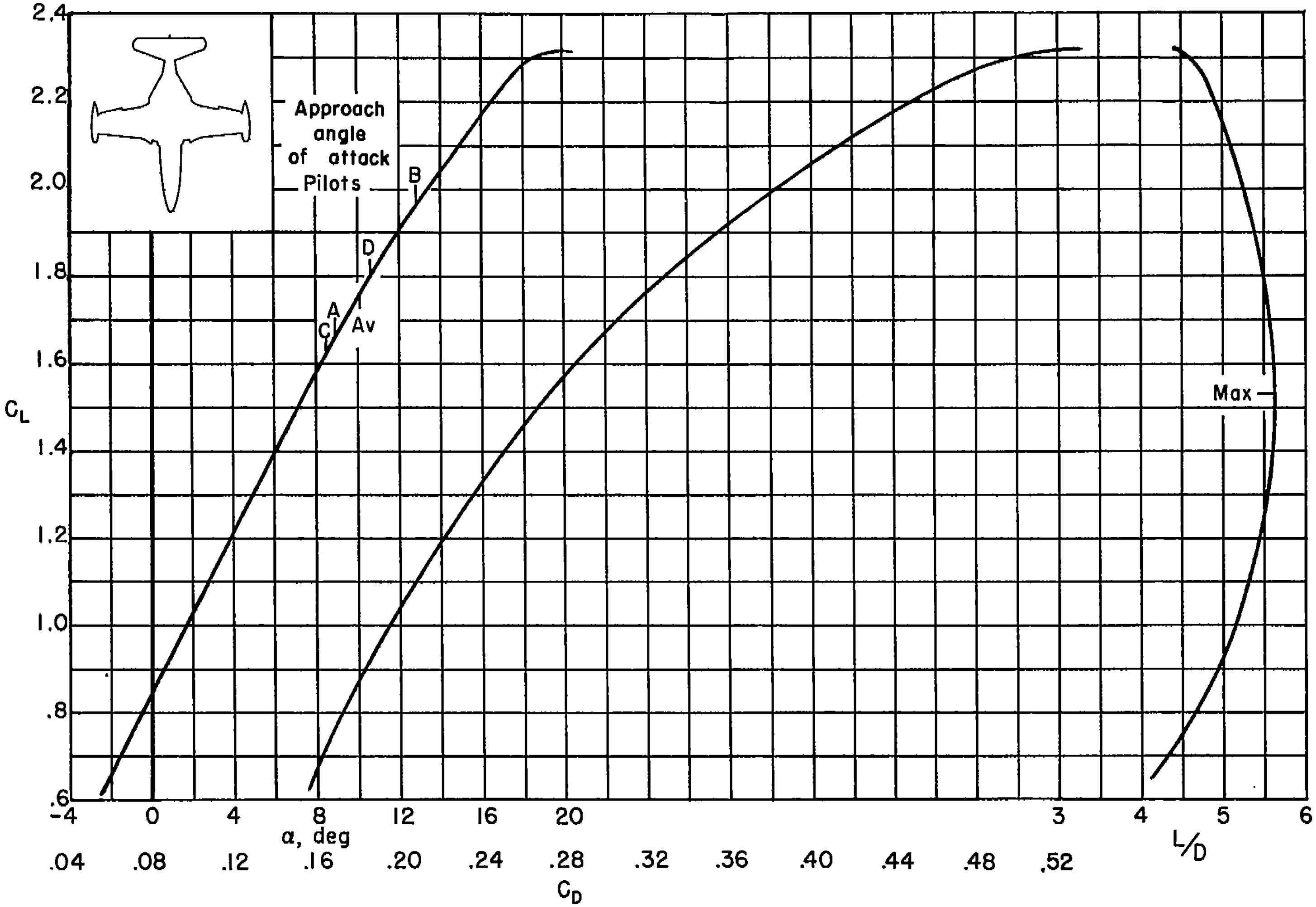


(b) Variation of airplane drag with velocity.



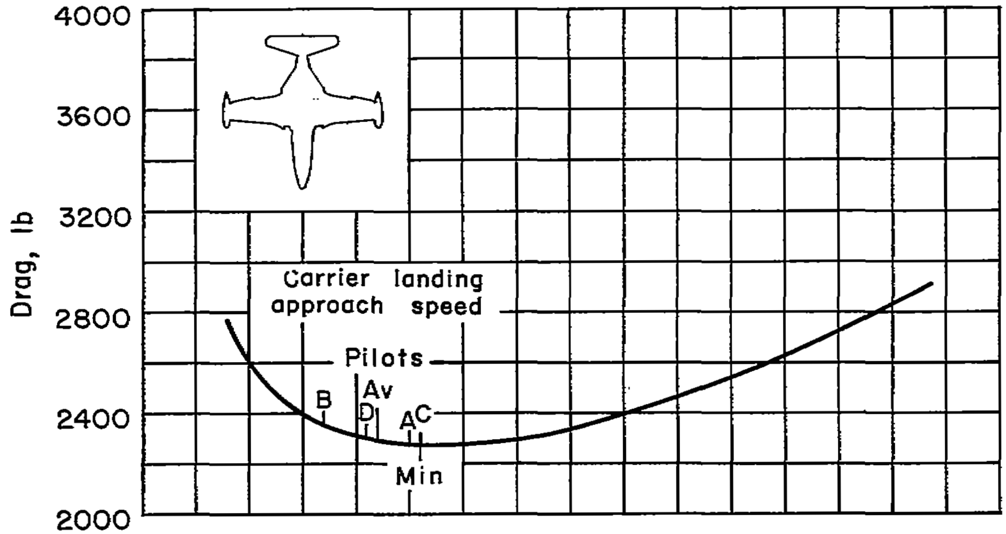
(c) Variation of horsepower required for level flight with velocity.

Figure 13.- Concluded.

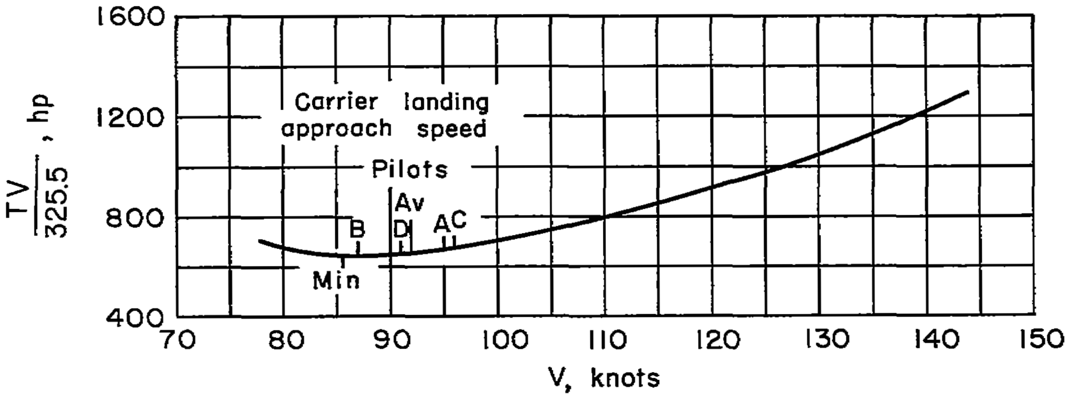


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 14.- Aerodynamic characteristics of the F9F-4 airplane; plain flap, $\delta_{f_{inboard}} = 40^\circ$, $\delta_{f_{outboard}} = 45^\circ$, leading-edge flap, blowing-flap BLC (config. 6a).

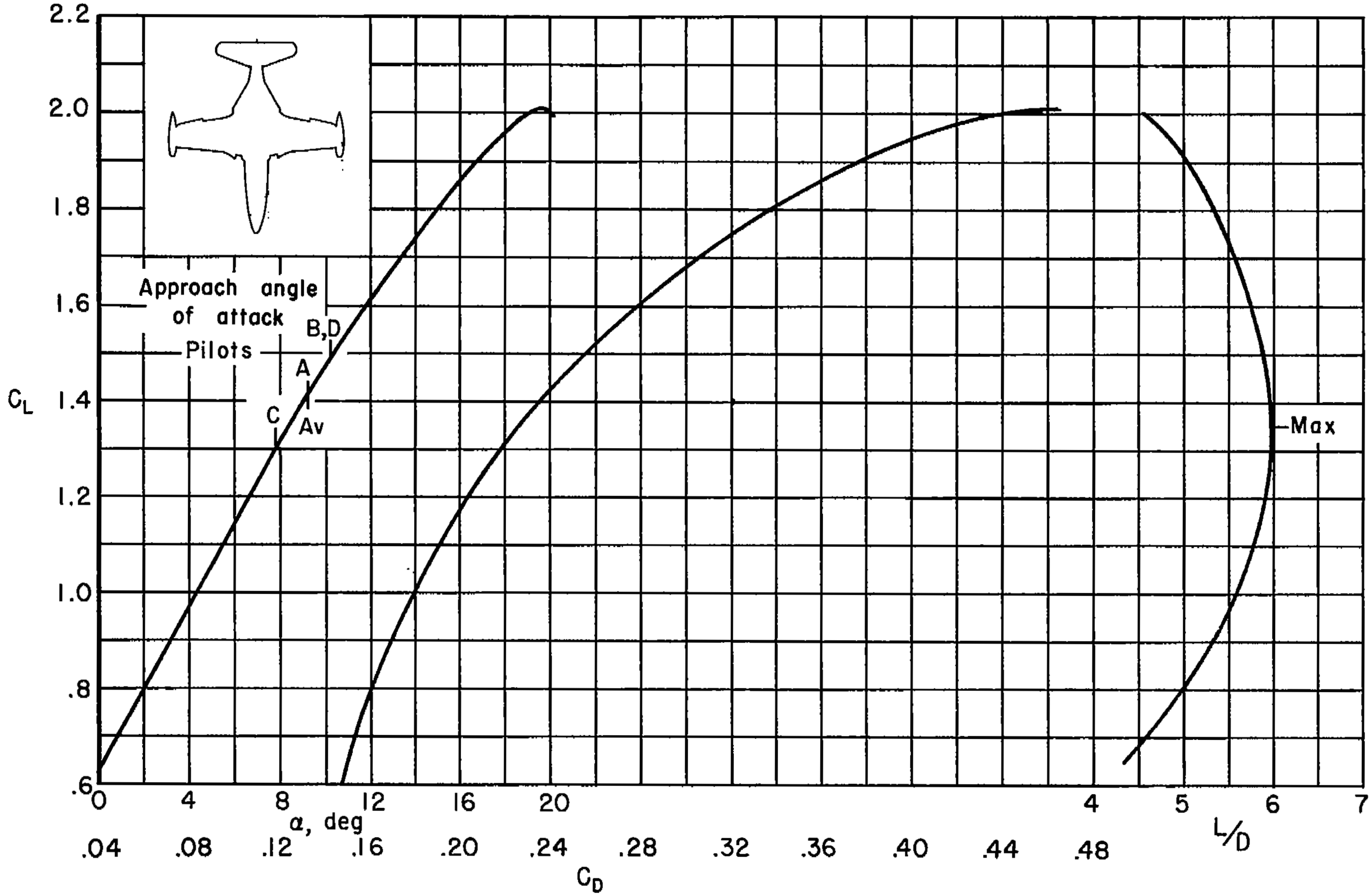


(b) Variation of airplane drag with velocity.



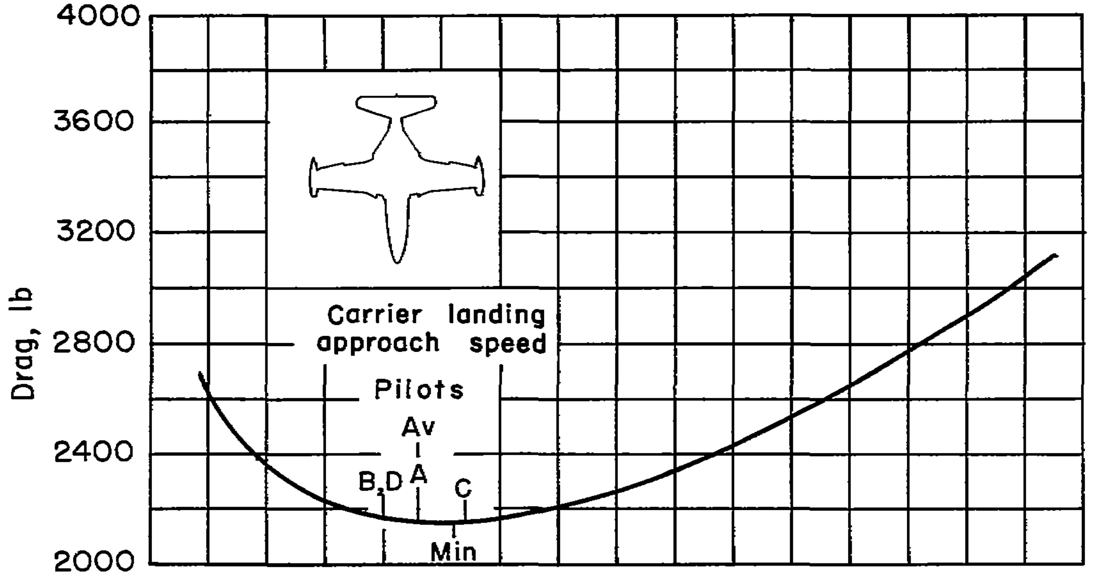
(c) Variation of horsepower required for level flight with velocity.

Figure 14.- Concluded.

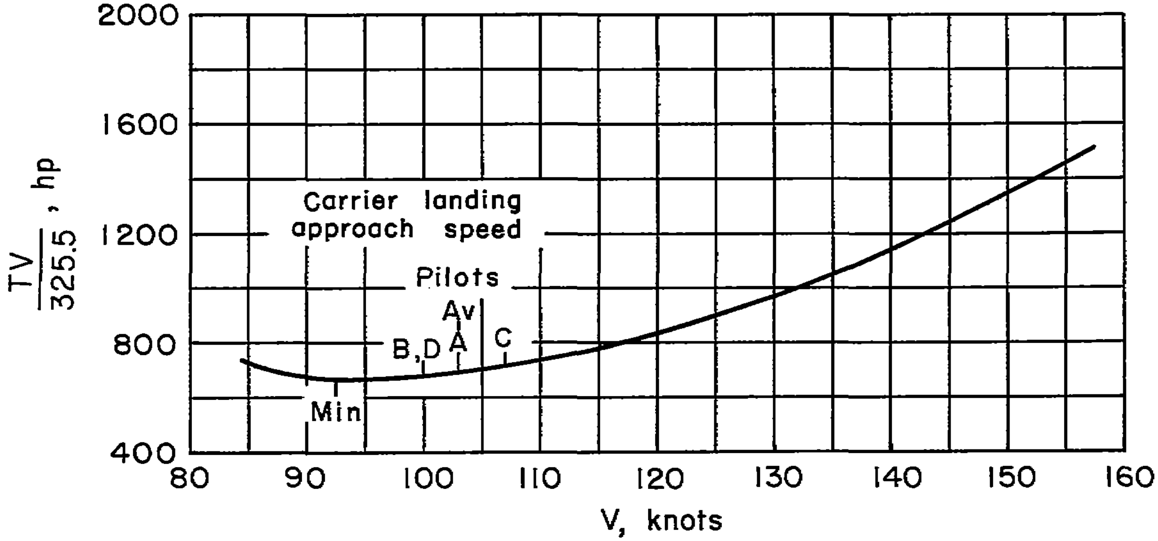


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 15.- Aerodynamic characteristics of the F9F-4 airplane; plain flap, $\delta_{f_{inboard}} = 40^{\circ}$, $\delta_{f_{outboard}} = 45^{\circ}$, leading-edge flap (config. 6b).

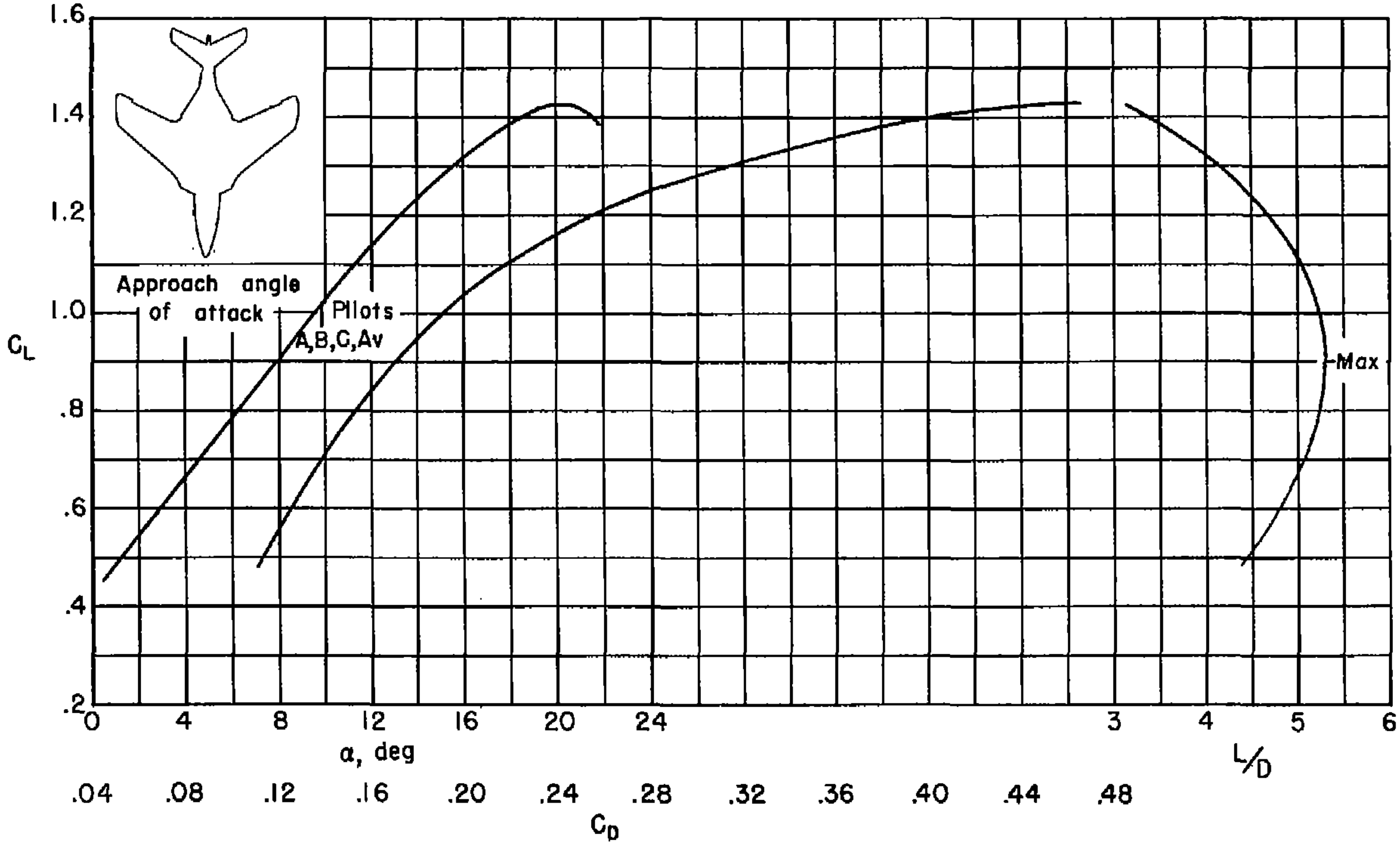


(b) Variation of airplane drag with velocity.



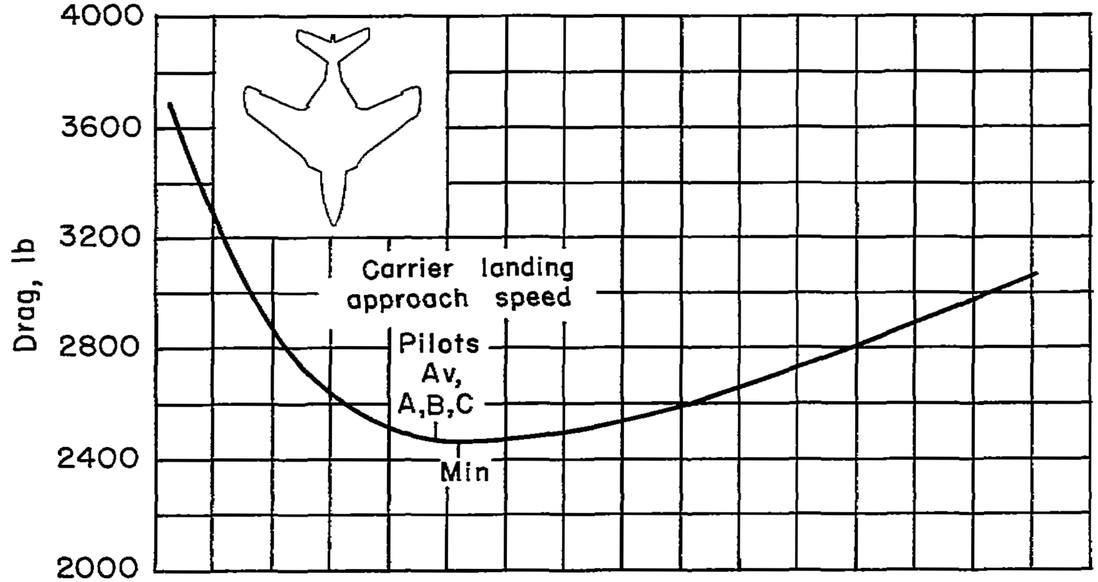
(c) Variation of horsepower required for level flight with velocity.

Figure 15.- Concluded.

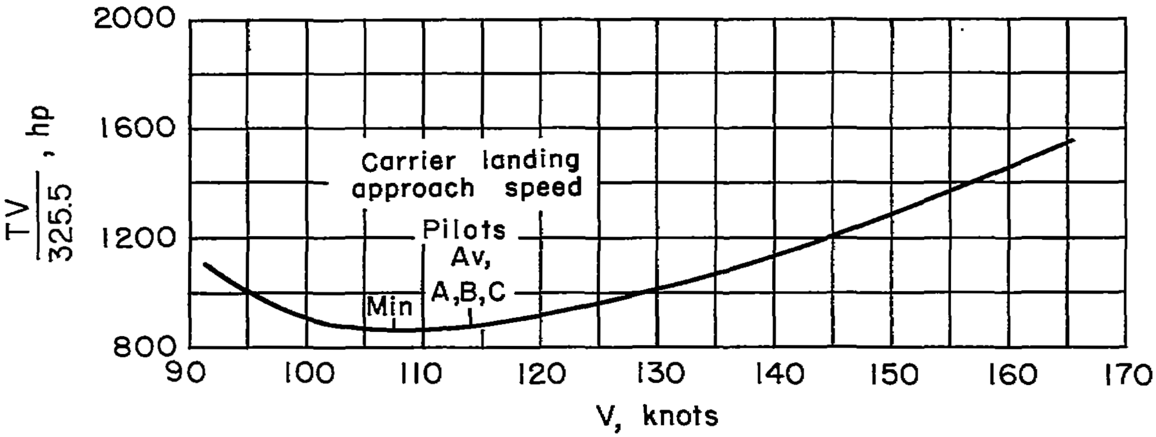


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 16.- Aerodynamic characteristics of the F9F-6 airplane; plain flap, $\delta_{f_{inboard}} = 40^{\circ}$, $\delta_{f_{outboard}} = 30^{\circ}$, leading-edge slats (config. 7).

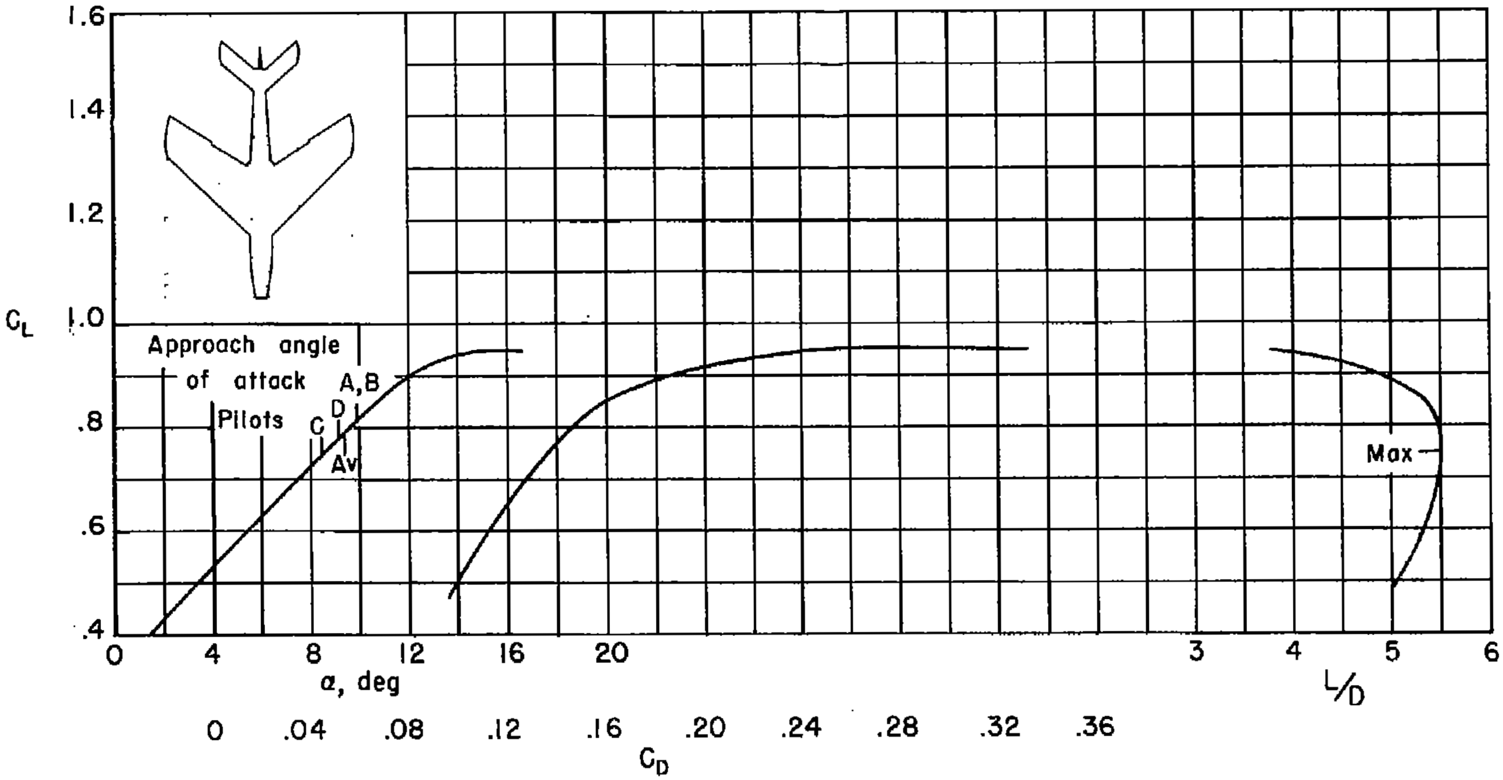


(b) Variation of airplane drag with velocity.



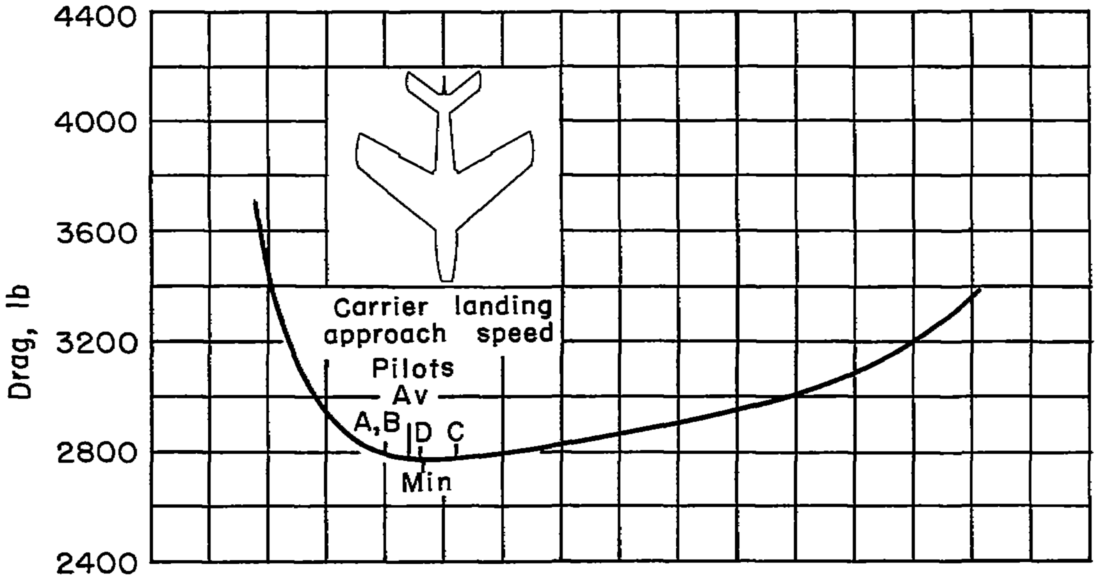
(c) Variation of horsepower required for level flight with velocity.

Figure 16.- Concluded.

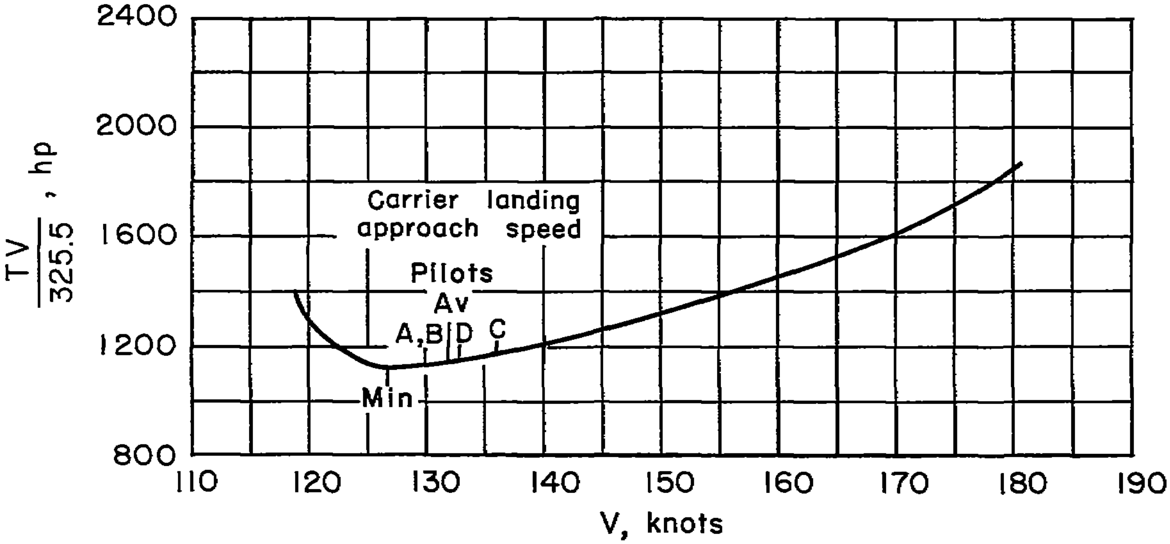


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 17.- Aerodynamic characteristics of the F-84F airplane; plain flap, $\delta_f = 40^\circ$ (config. 8a).

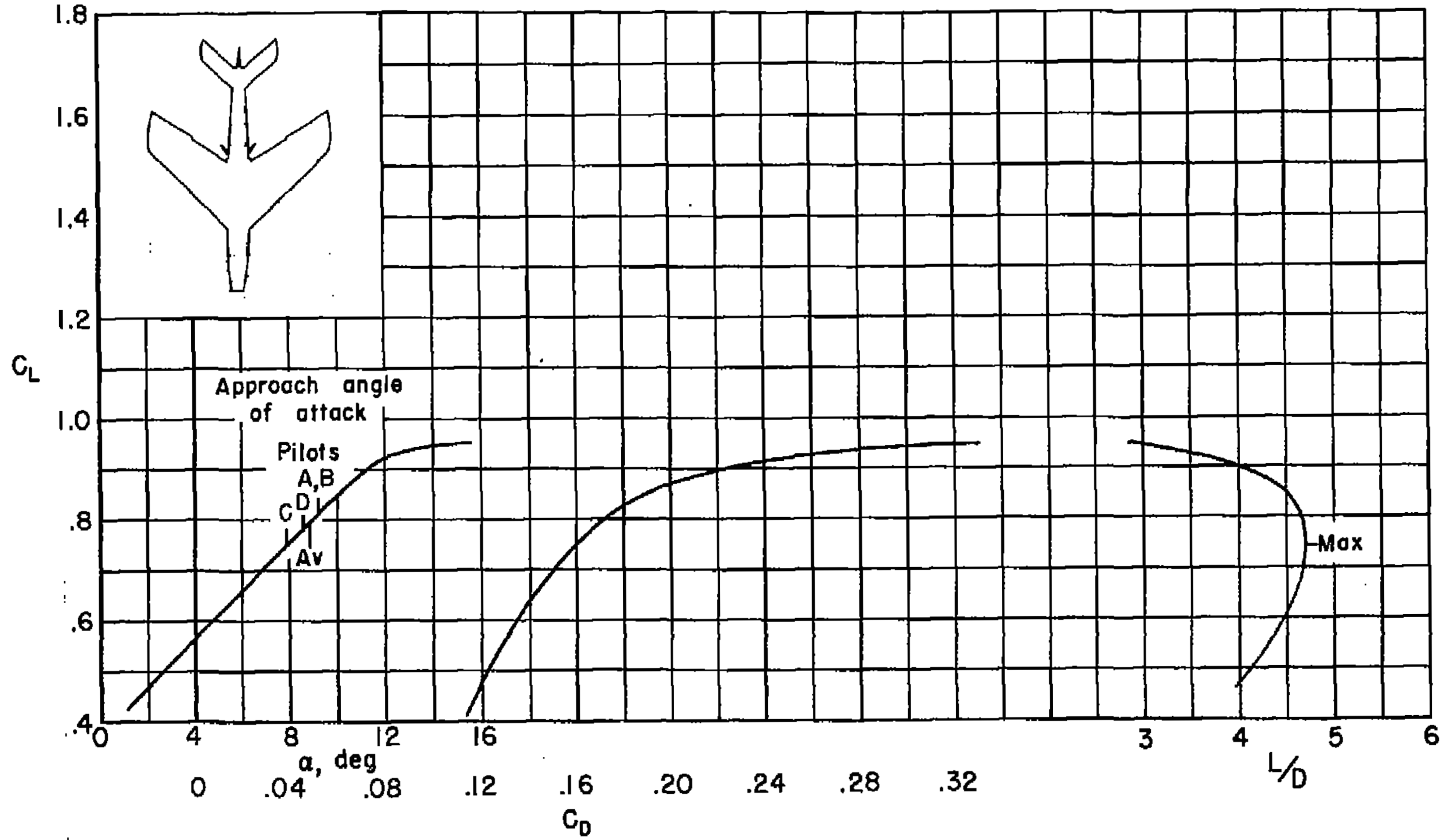


(b) Variation of airplane drag with velocity.



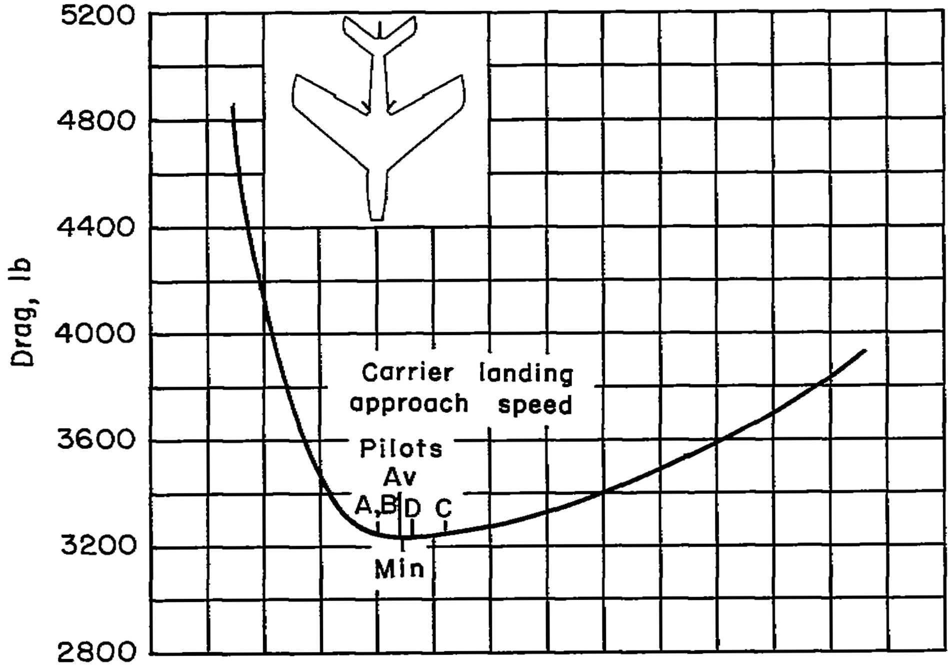
(c) Variation of horsepower required for level flight with velocity.

Figure 17.- Concluded.

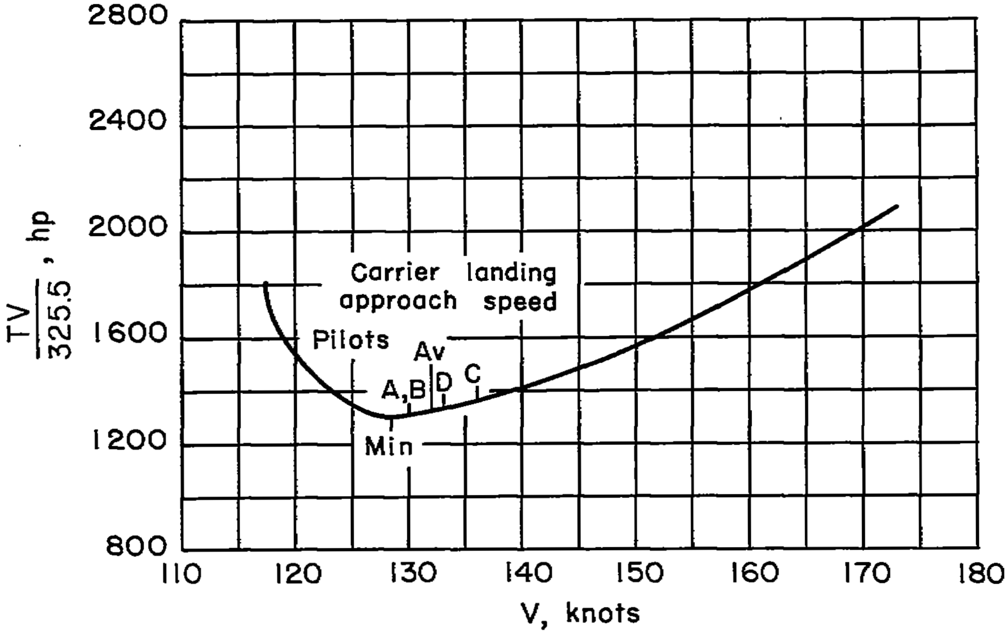


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 18.- Aerodynamic characteristics of the F-84F airplane; plain flap, $\delta_f = 40^{\circ}$, speed brakes (config. 8b).

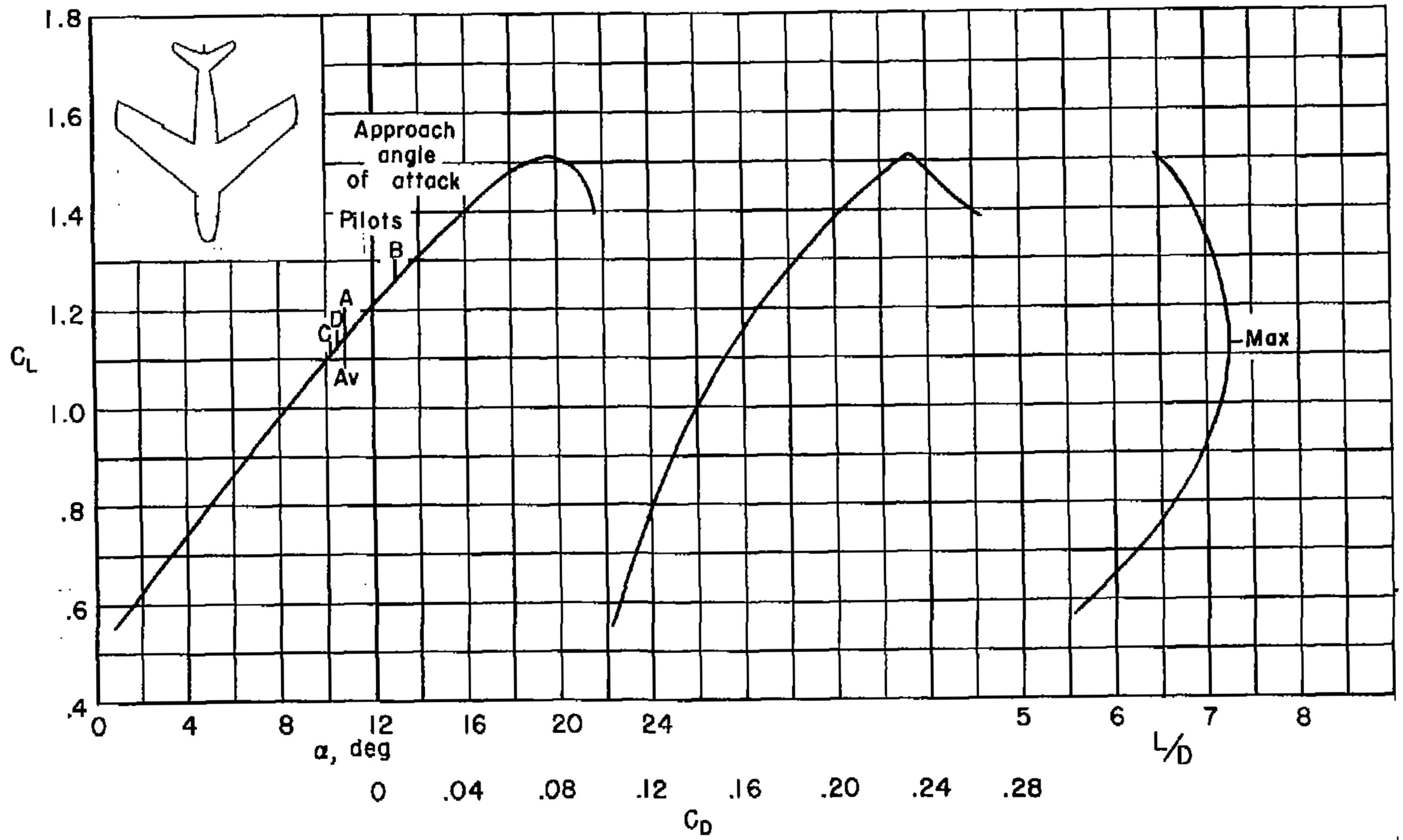


(b) Variation of airplane drag with velocity.



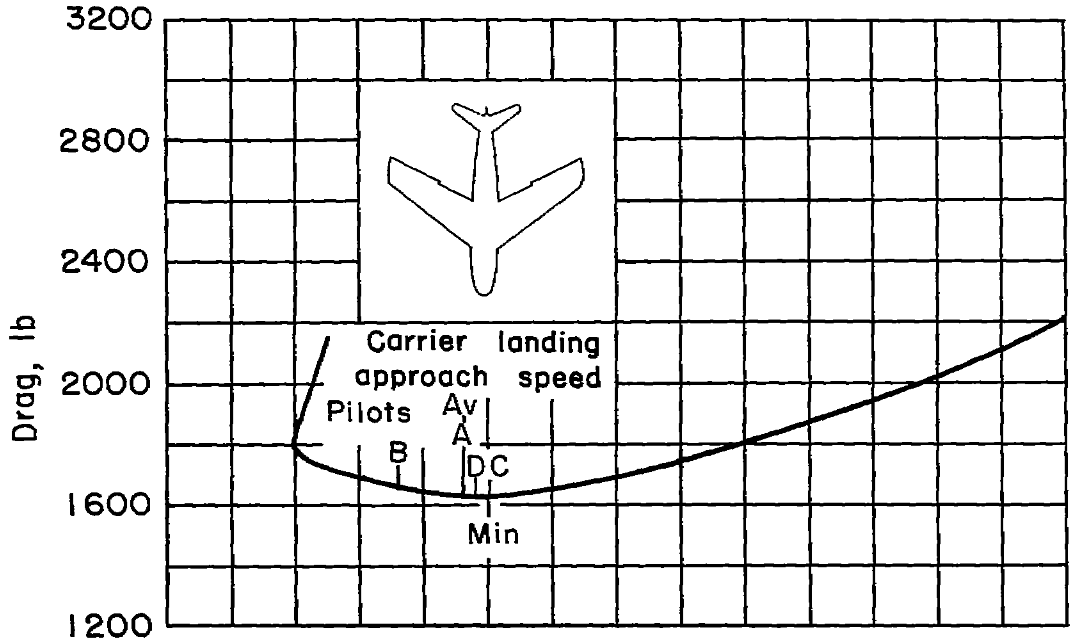
(c) Variation of horsepower required for level flight with velocity.

Figure 18.- Concluded.

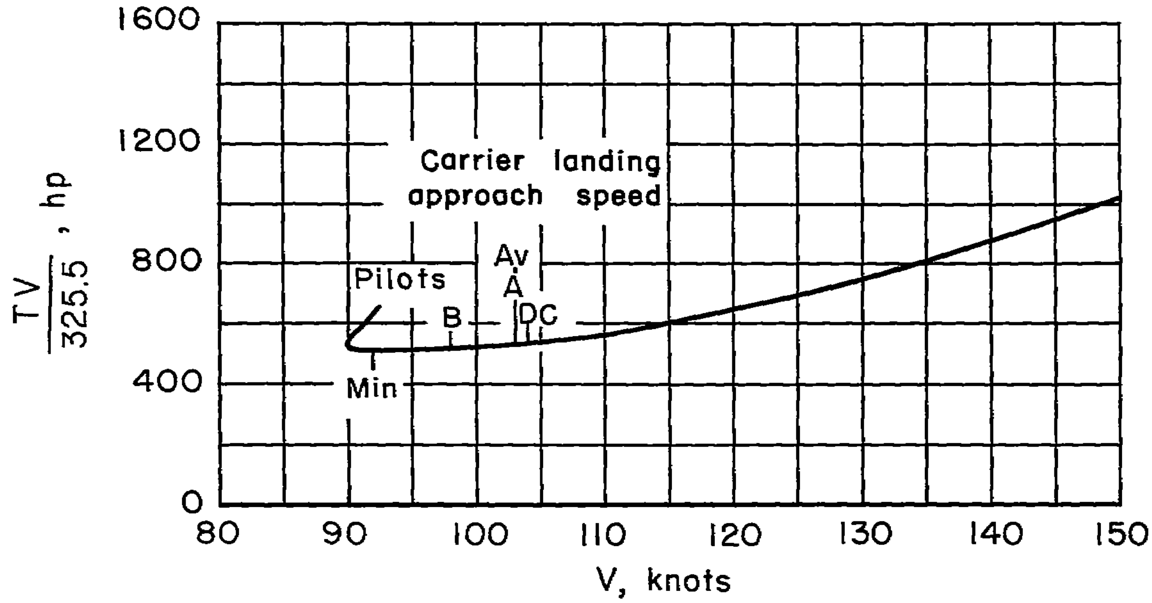


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 19.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 55^\circ$, leading-edge slats, suction-flap BLC (config. 9a).



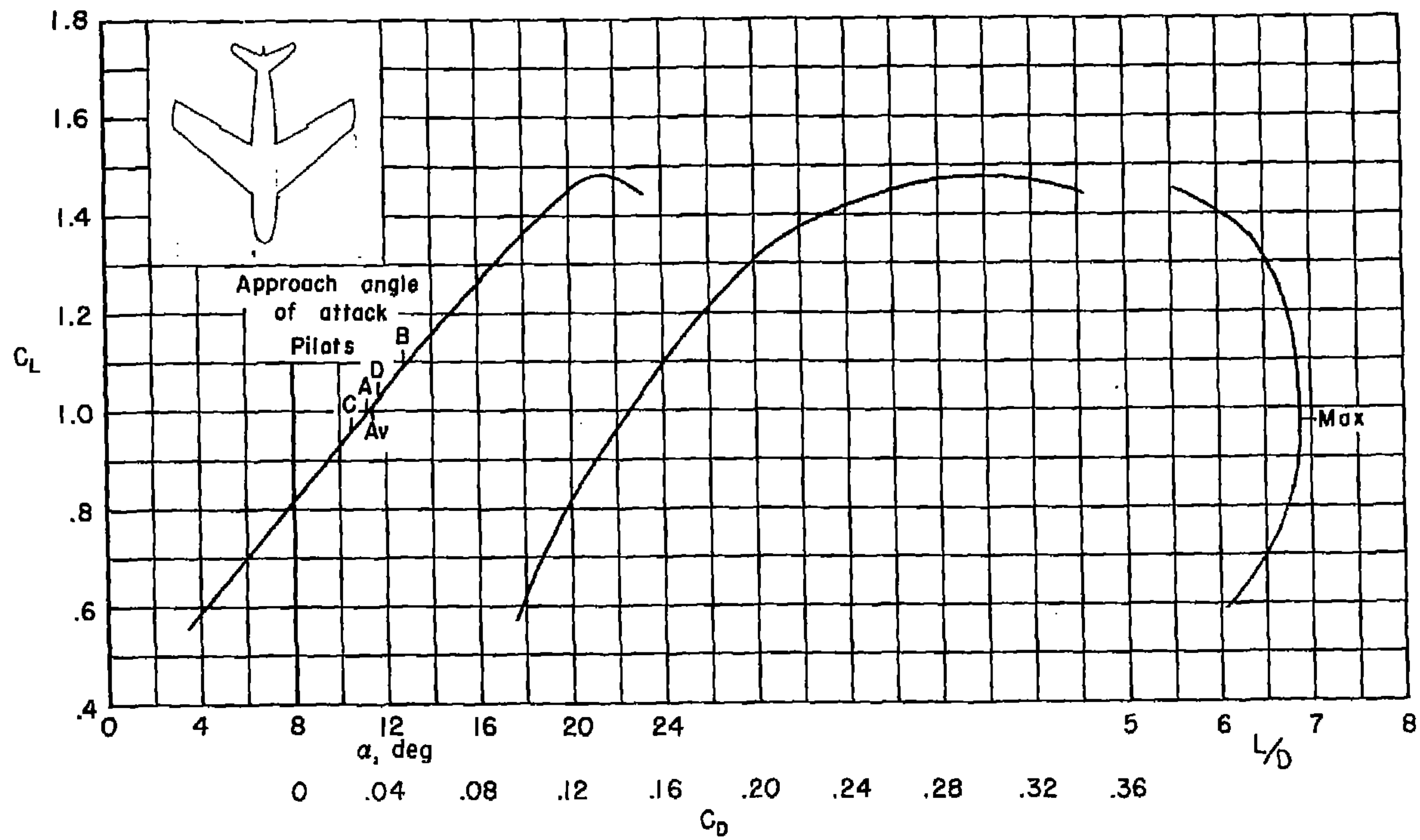
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

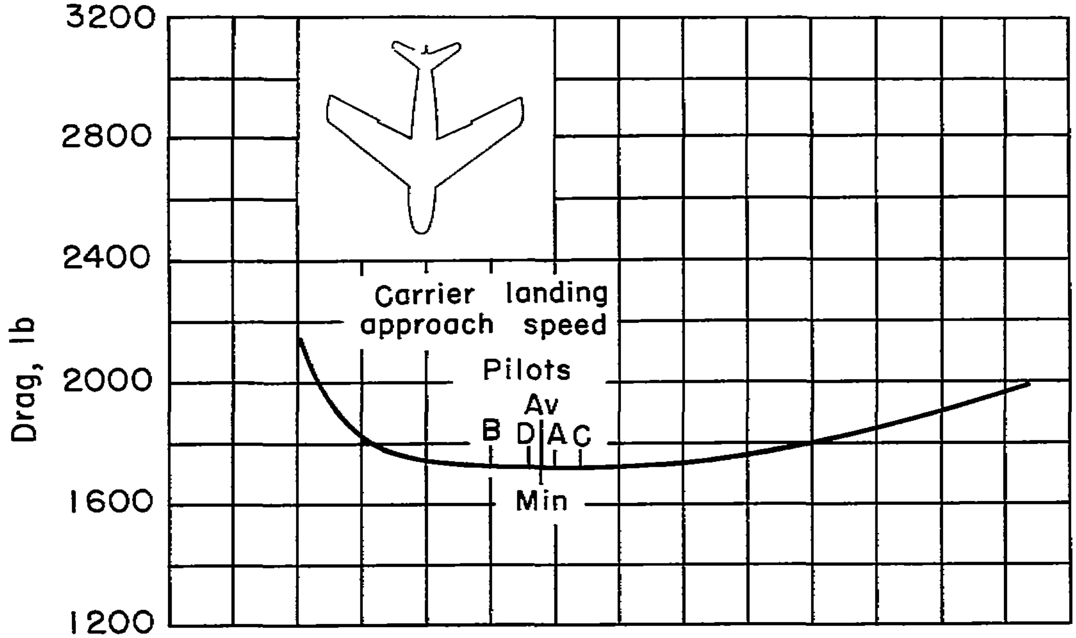
Figure 19.- Concluded.

[redacted]

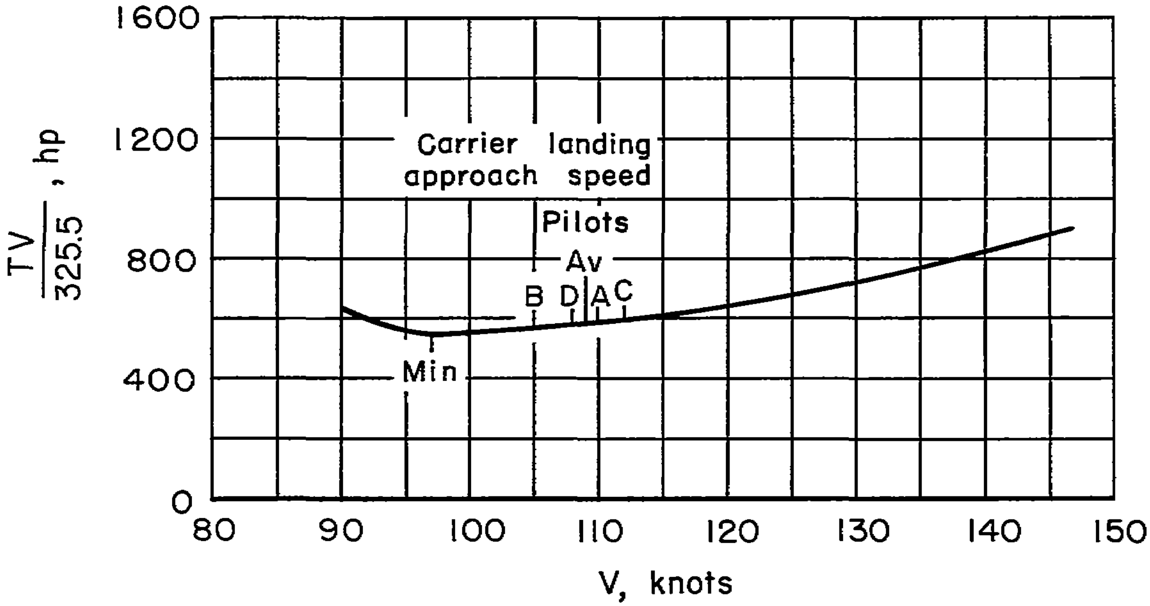


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 20.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 55^{\circ}$, leading-edge slats (config. 9b).

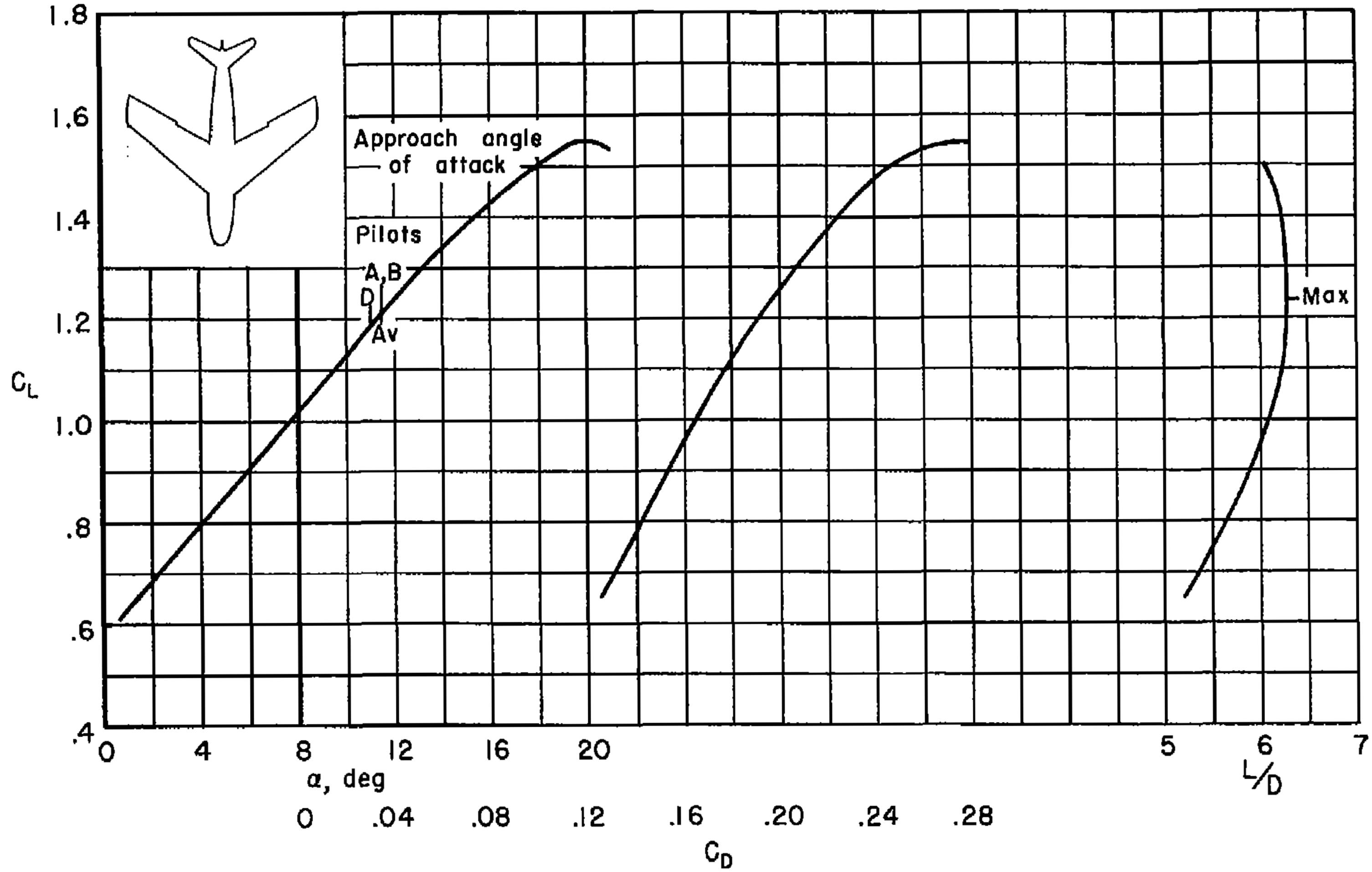


(b) Variation of airplane drag with velocity.



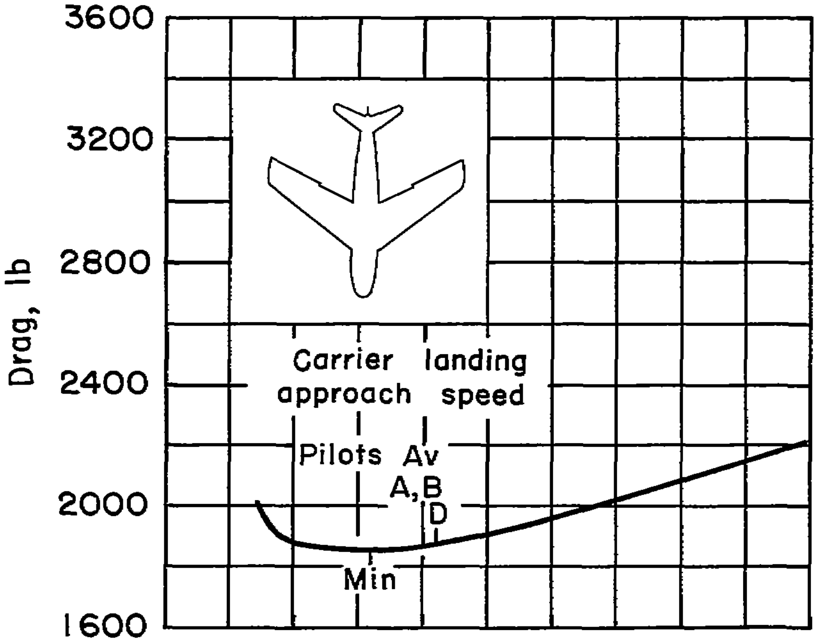
(c) Variation of horsepower required for level flight with velocity.

Figure 20.- Concluded.

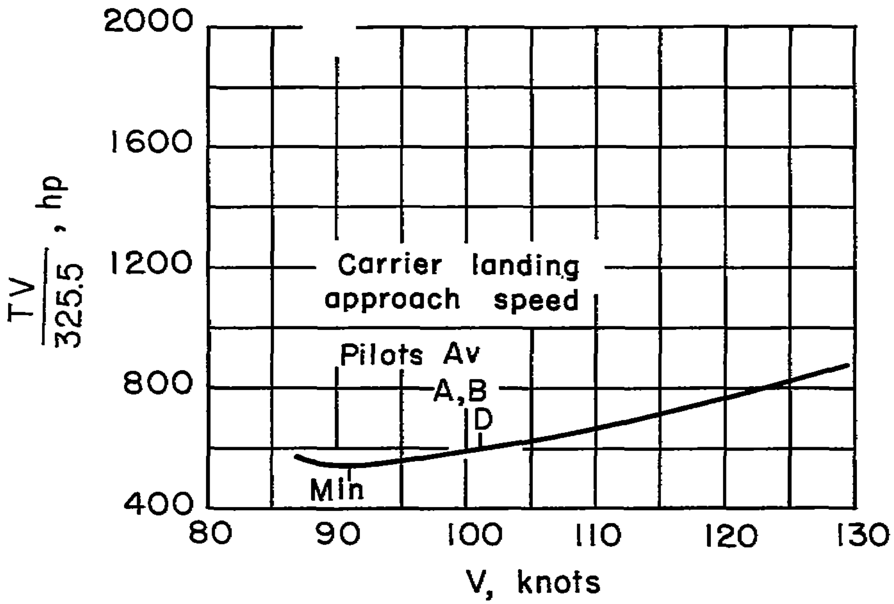


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 21.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 64^\circ$, leading-edge slats, suction-flap BLC (config. 9c).



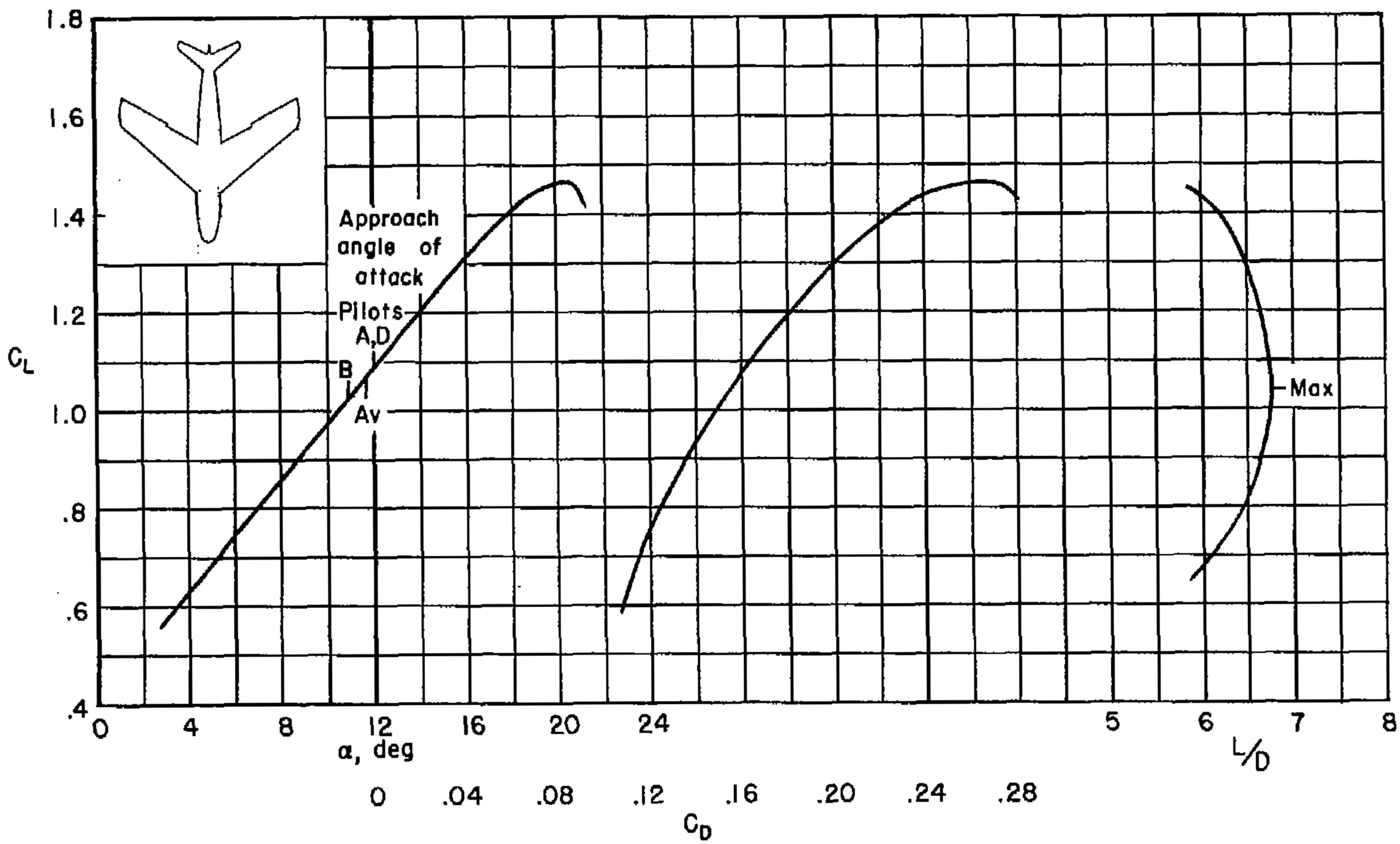
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

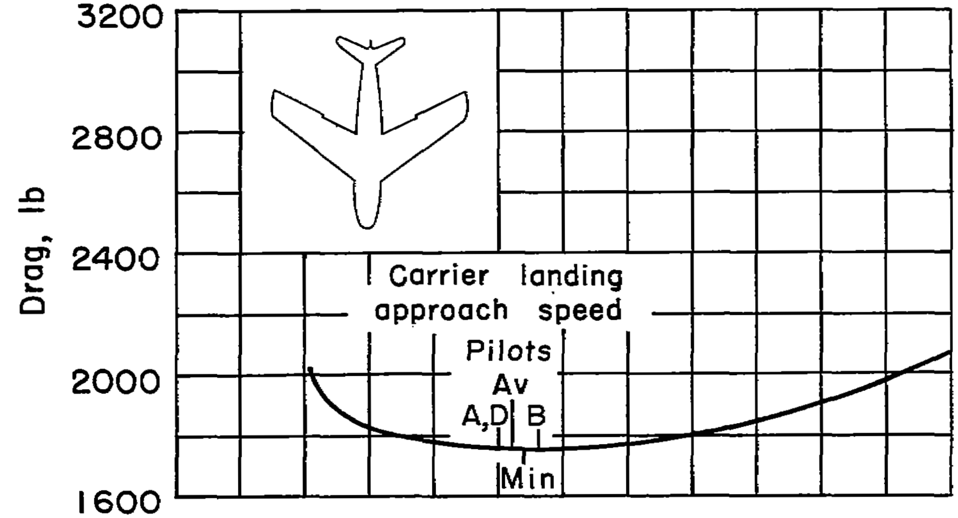
Figure 21.- Concluded.

[redacted]

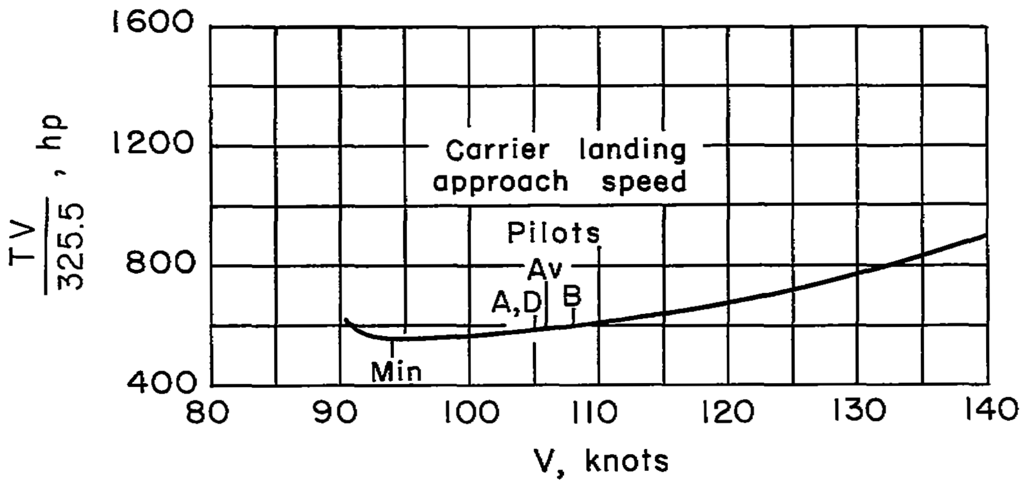


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 22.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 64^{\circ}$, leading-edge slats (config. 9d).

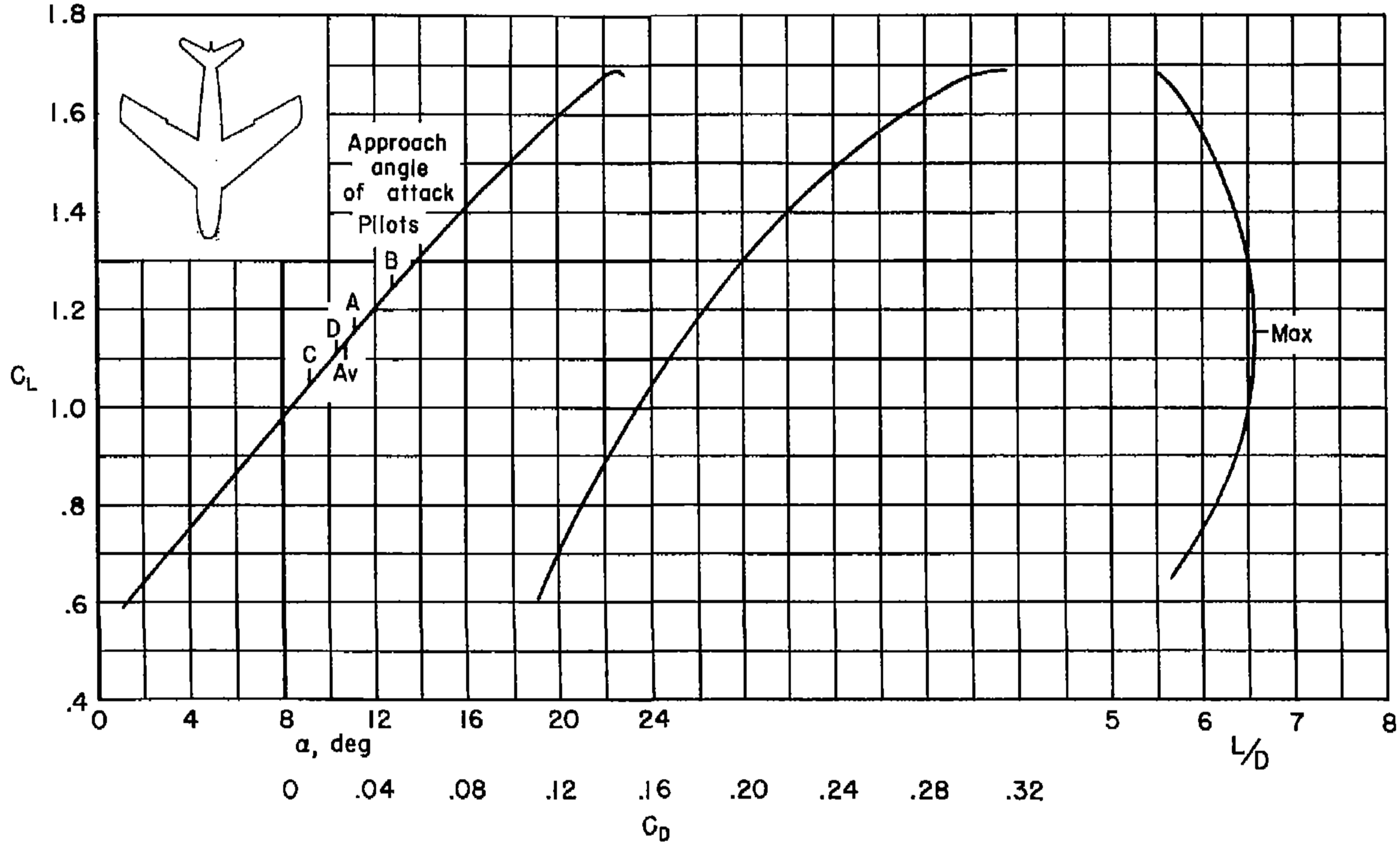


(b) Variation of airplane drag with velocity.



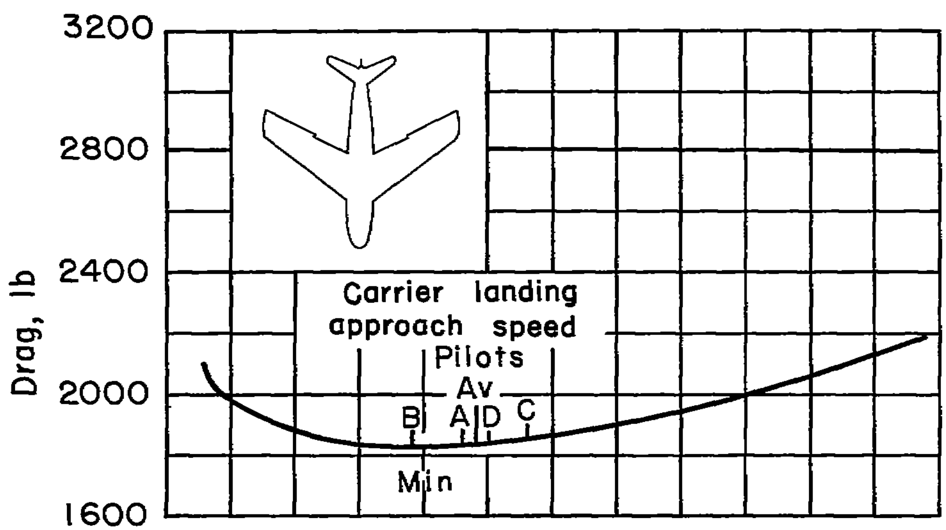
(c) Variation of horsepower required for level flight with velocity.

Figure 22.- Concluded.

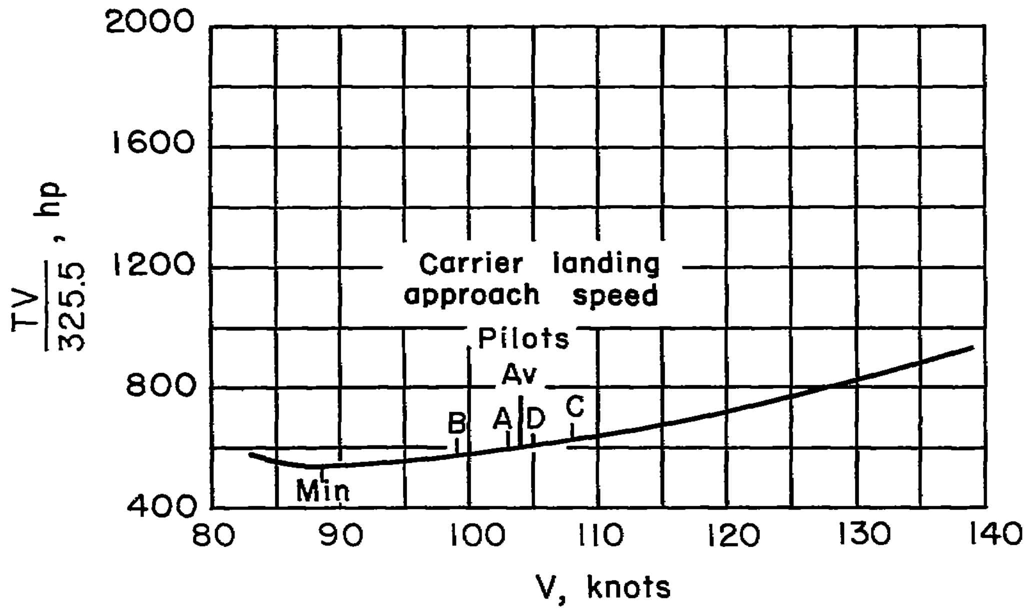


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 23.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 55^\circ$, leading-edge camber, suction-flap BLC (config. 10a).

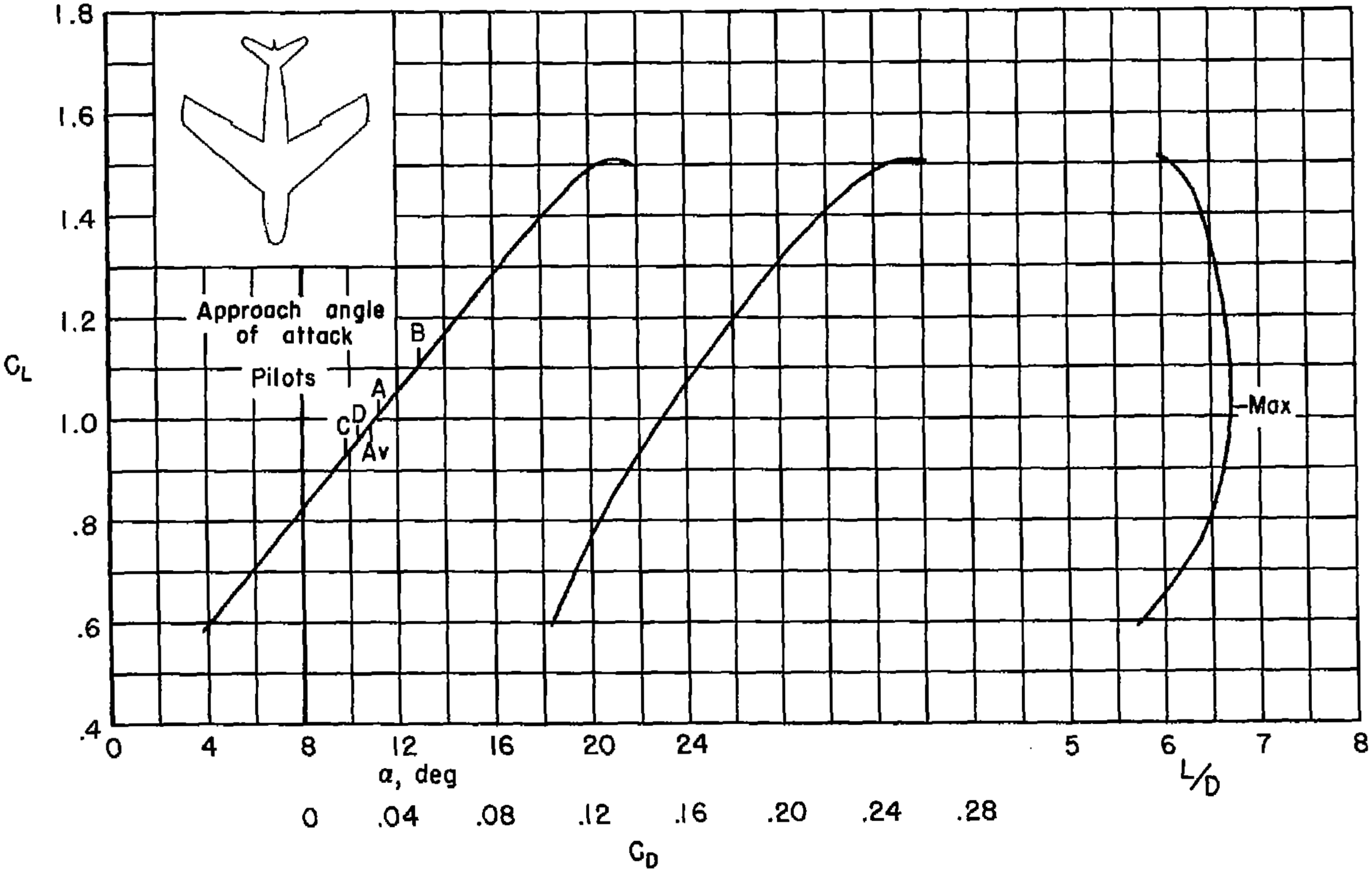


(b) Variation of airplane drag with velocity.



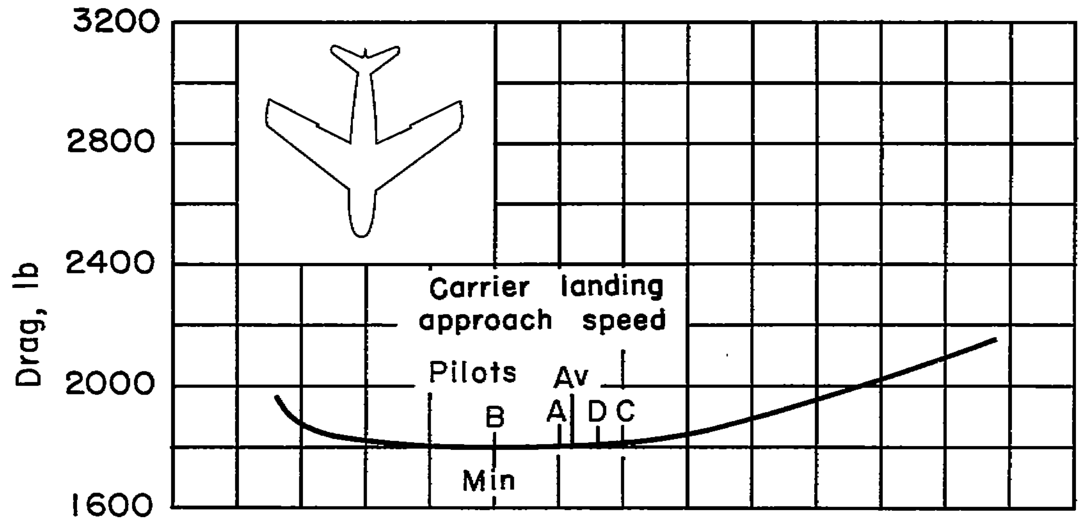
(c) Variation of horsepower required for level flight with velocity.

Figure 23.- Concluded.

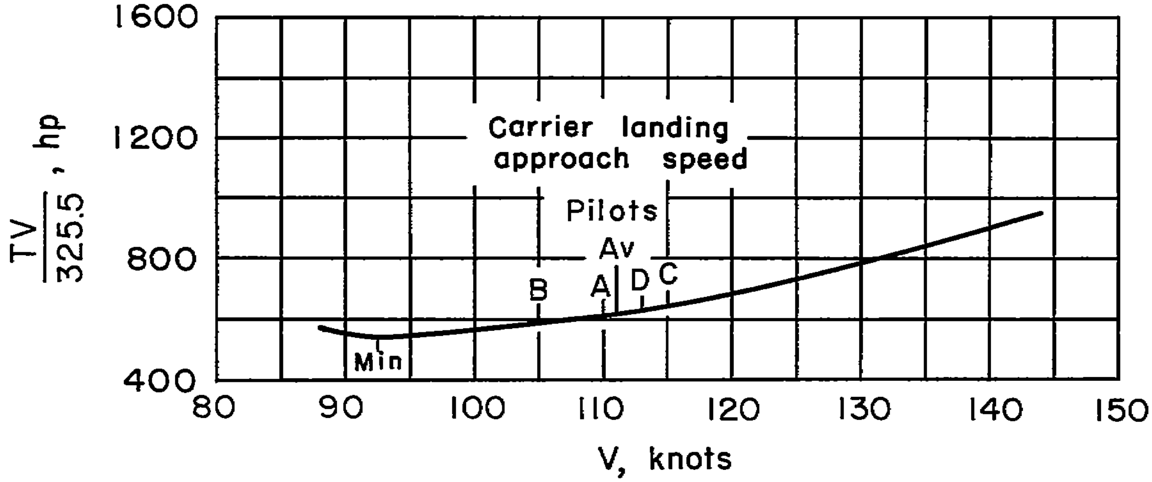


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 24.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 55^\circ$, leading-edge camber (config. 10b).

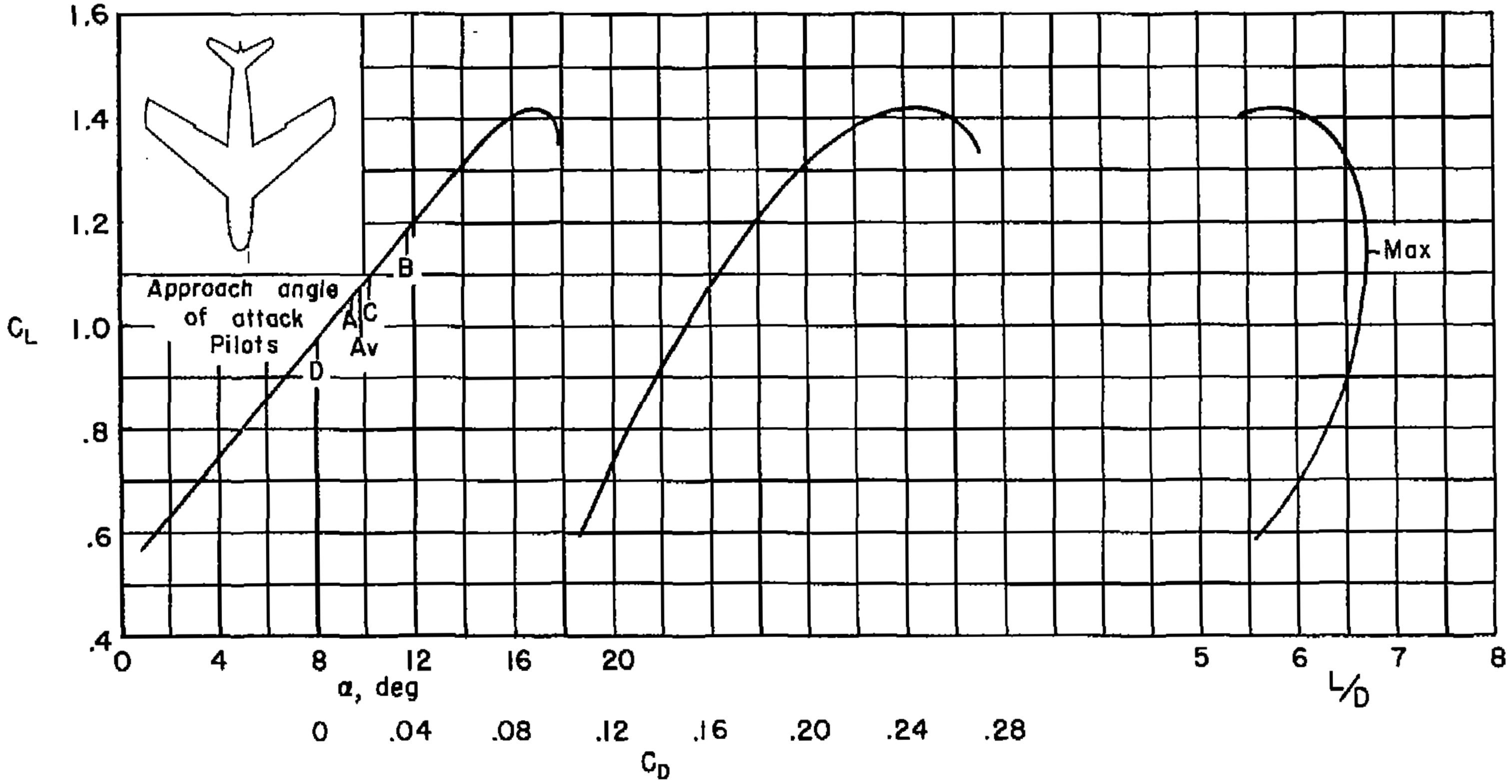


(b) Variation of airplane drag with velocity.



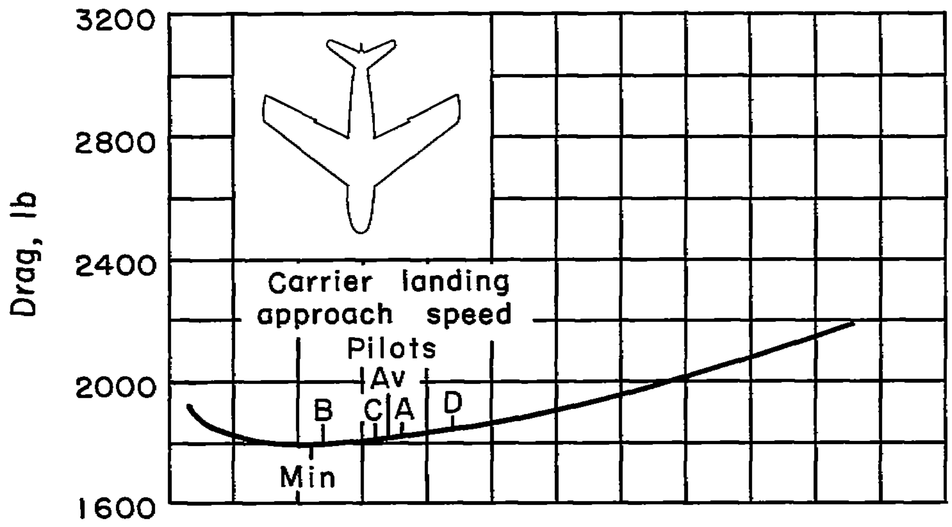
(c) Variation of horsepower required for level flight with velocity.

Figure 24.- Concluded.

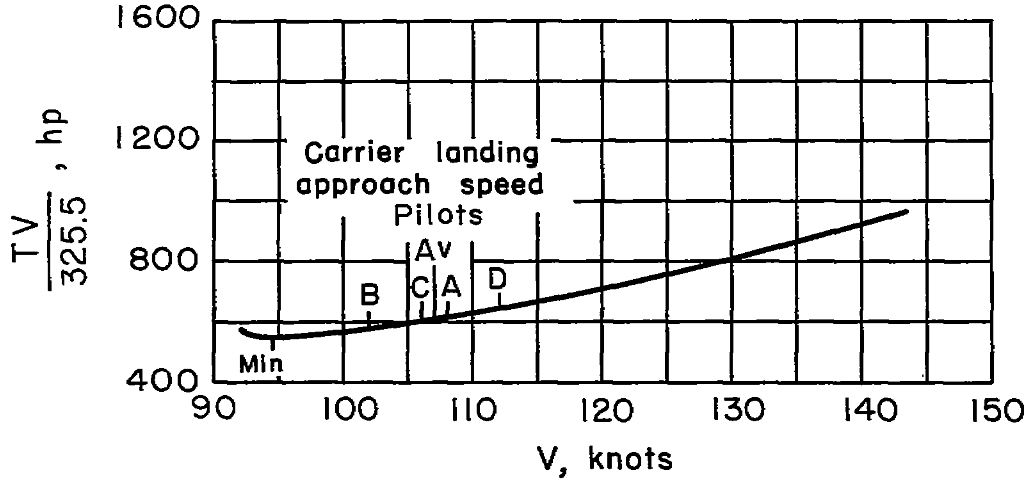


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 25.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 55^{\circ}$, leading-edge camber, fence, suction-flap BLC (config. 11a).

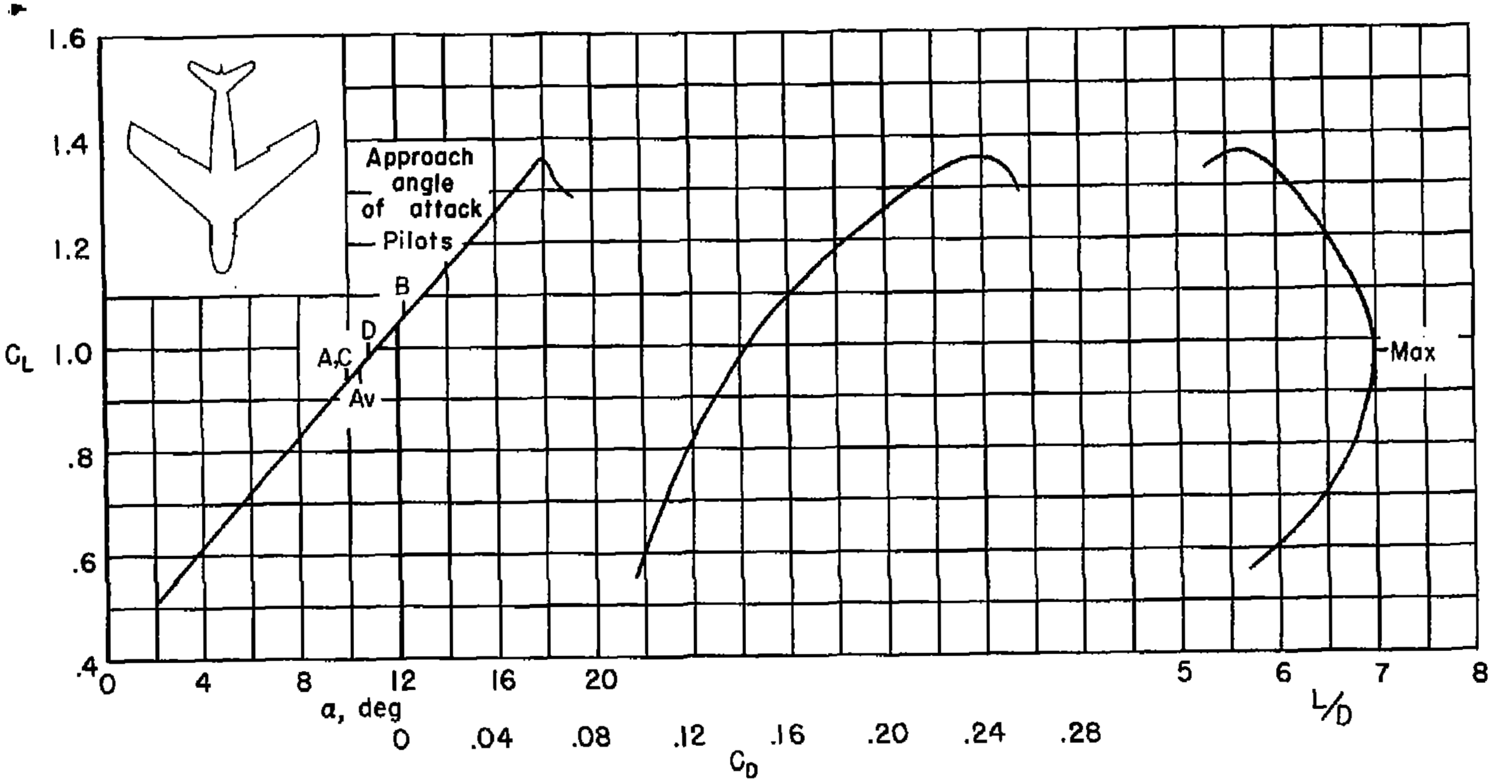


(b) Variation of airplane drag with velocity.



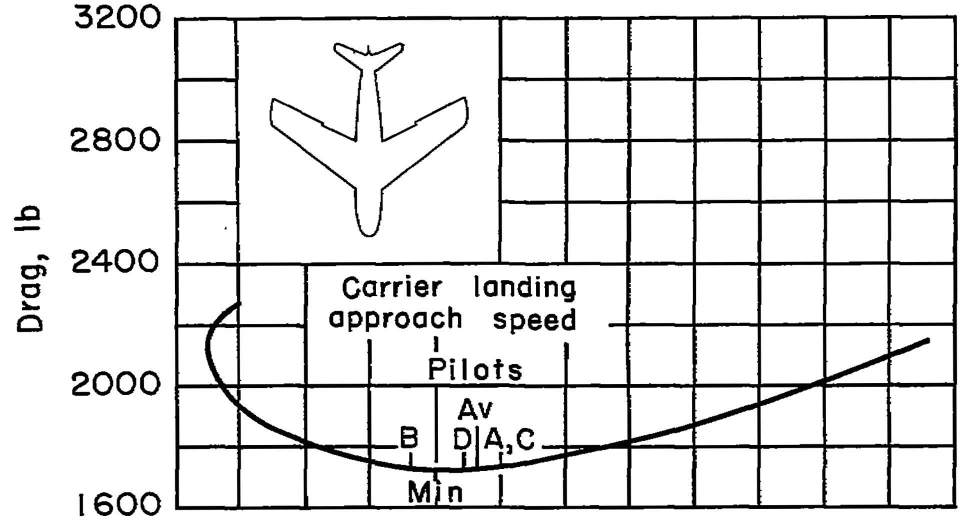
(c) Variation of horsepower required for level flight with velocity.

Figure 25.- Concluded.

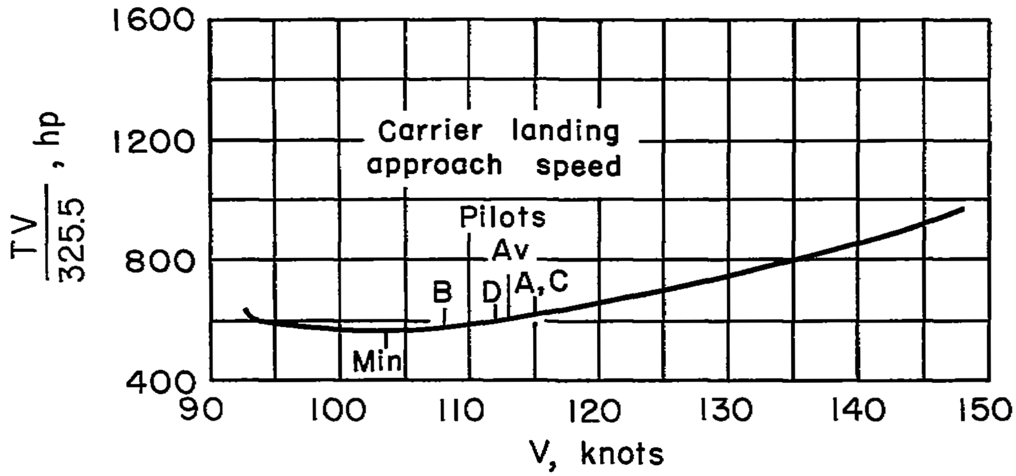


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 26.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 55^\circ$, leading-edge camber, fence (config. 11b).

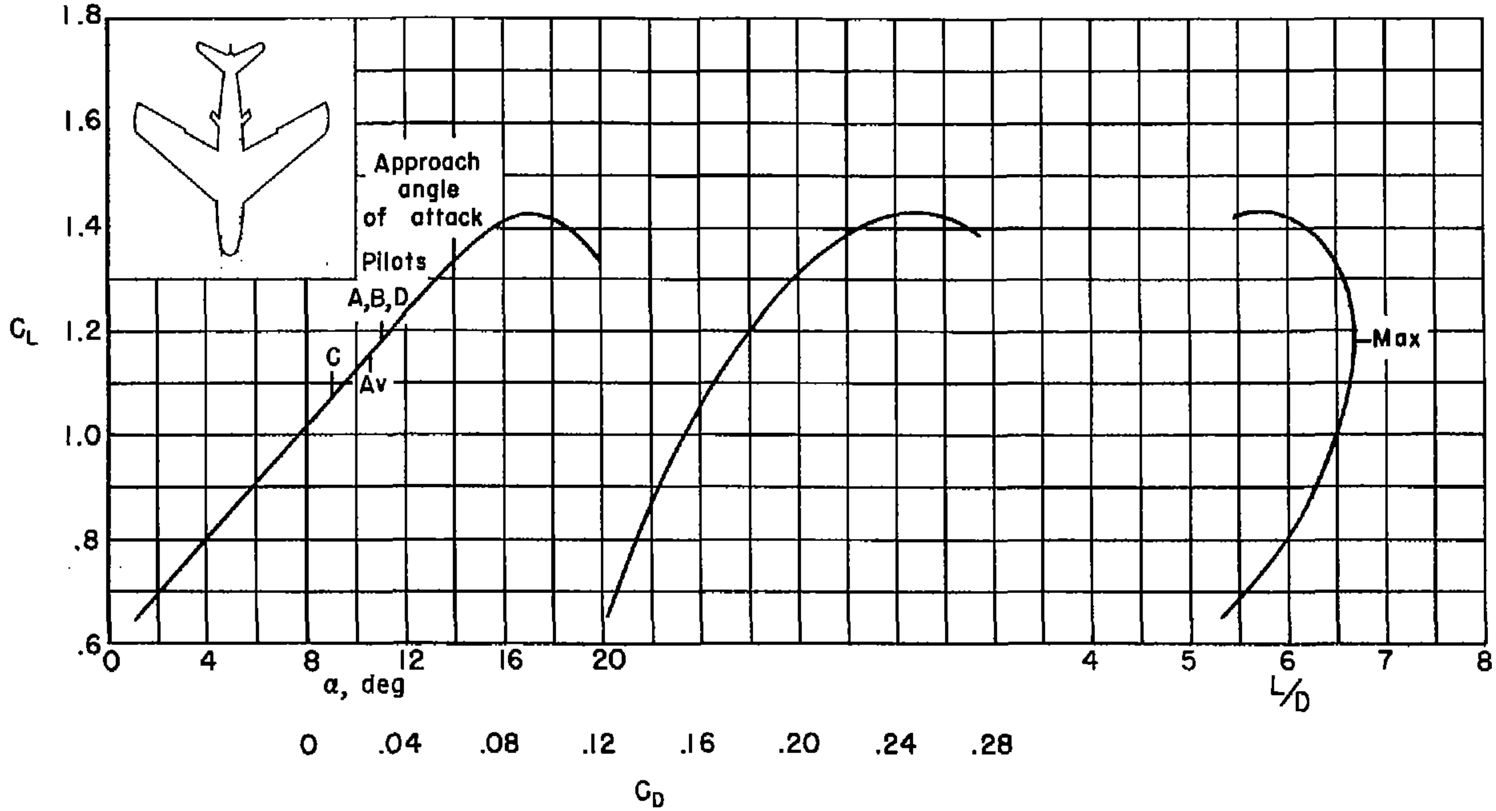


(b) Variation of airplane drag with velocity.



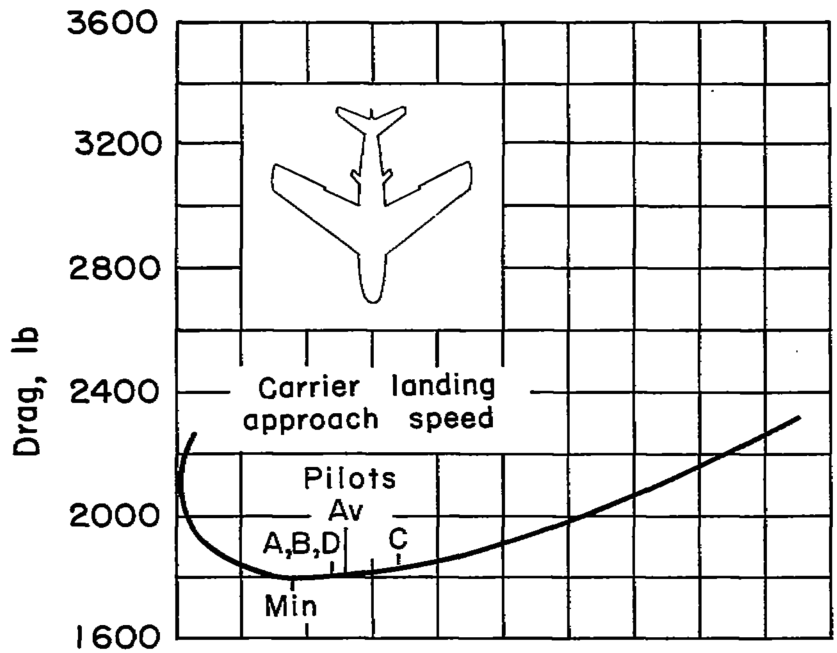
(c) Variation of horsepower required for level flight with velocity.

Figure 26.- Concluded.

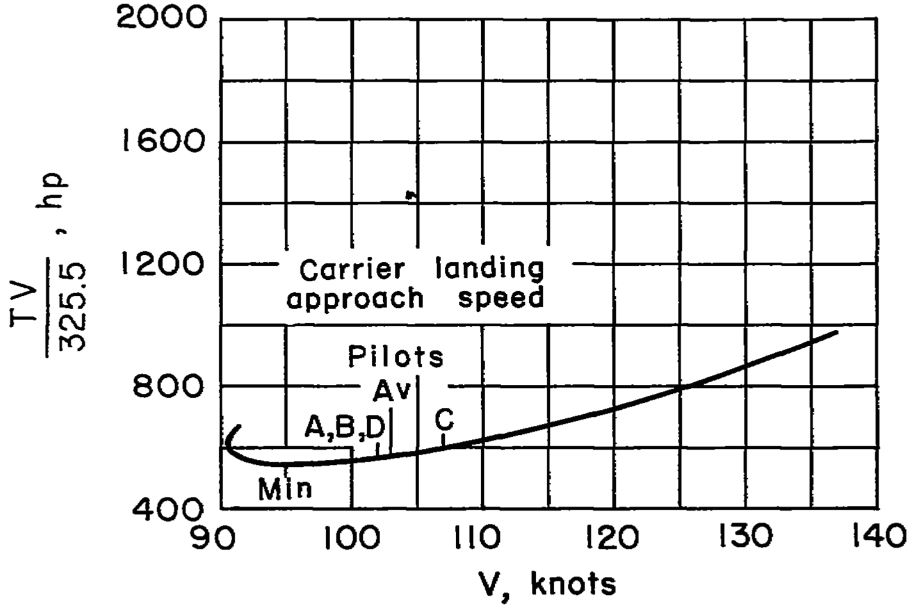


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 27.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 64^\circ$, leading-edge camber, fence, suction-flap BLC (config. 11c).



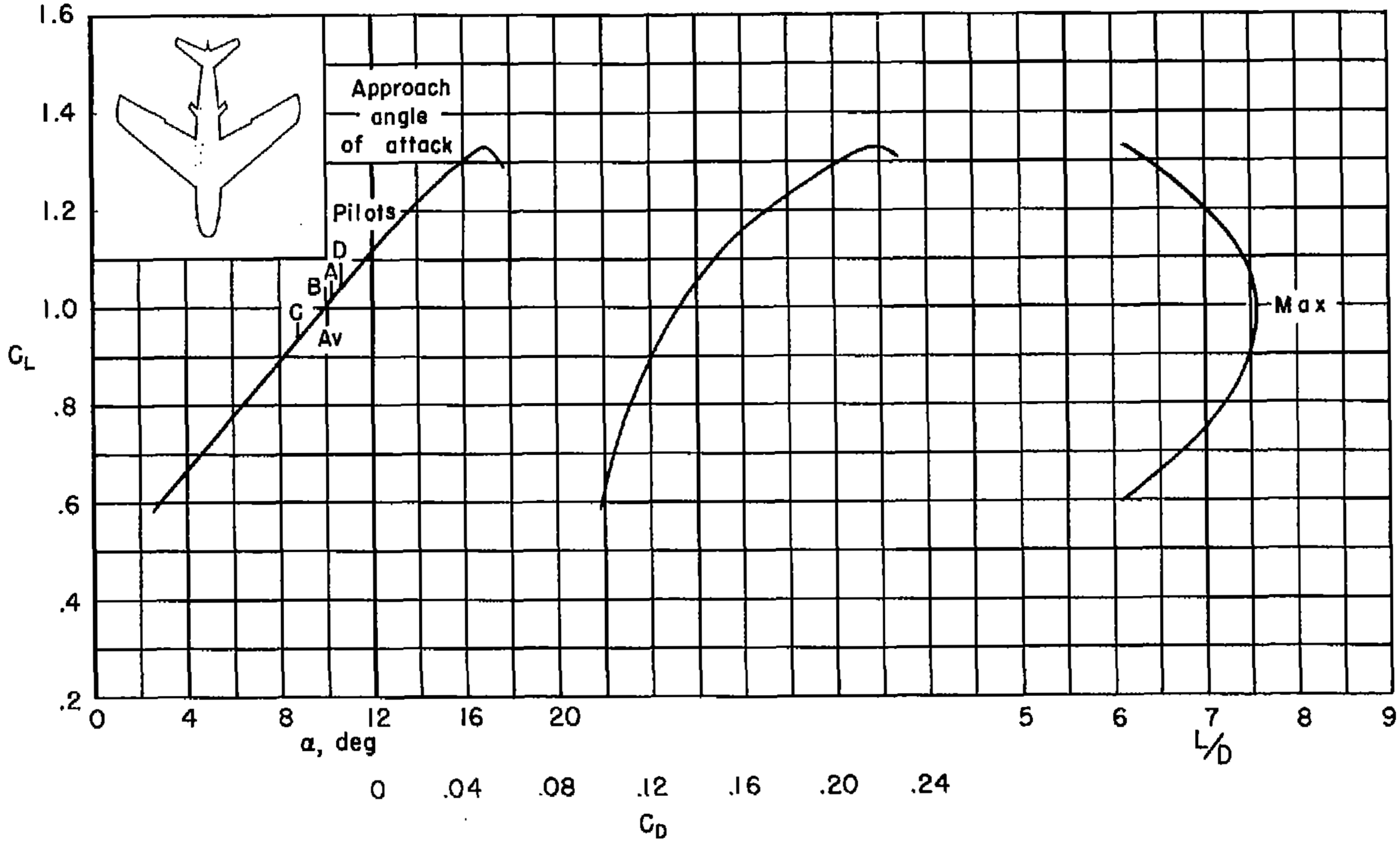
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 27.- Concluded.

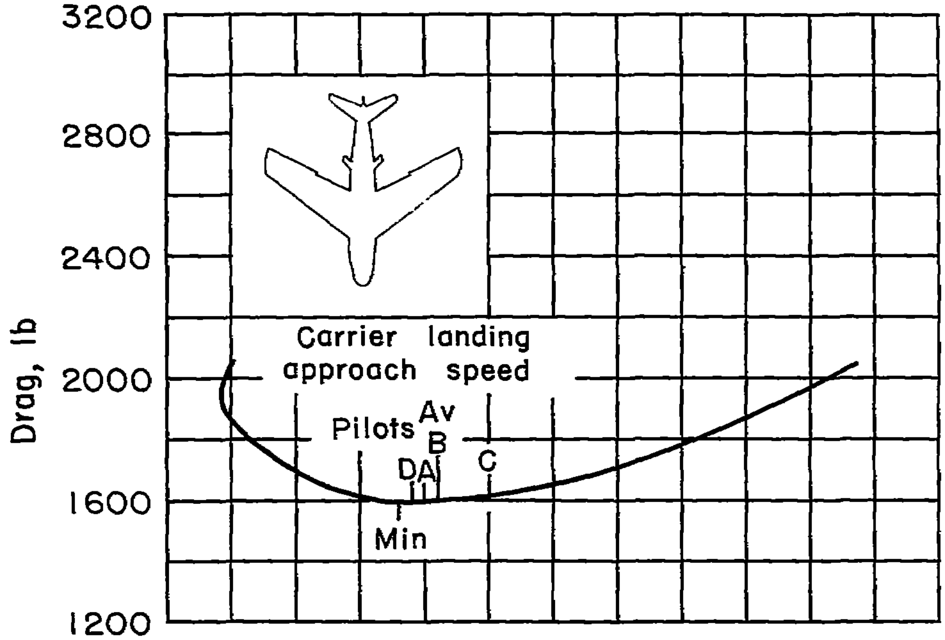
[redacted]



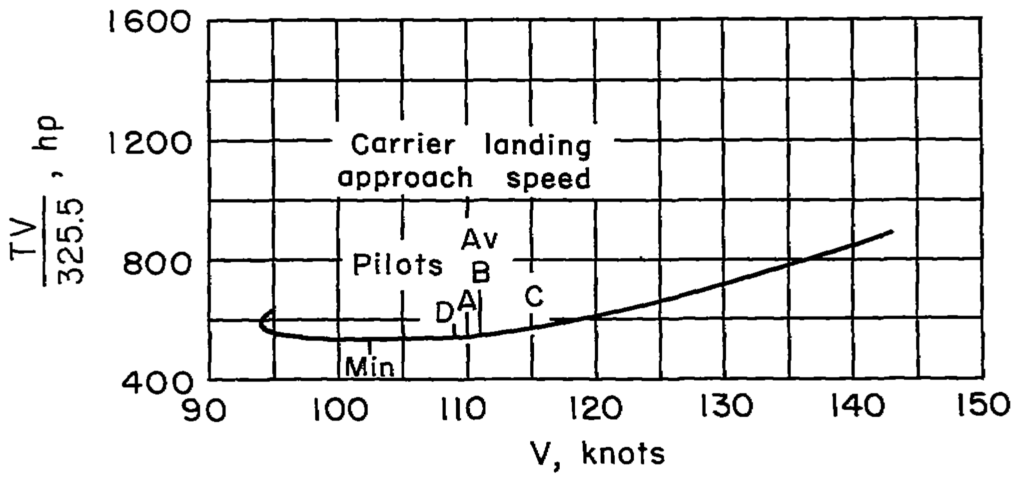
[redacted]

(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 28.- Aerodynamic characteristics of the F-86A airplane; plain flap, $\delta_f = 64^\circ$, leading-edge camber, fence (config. 11d).



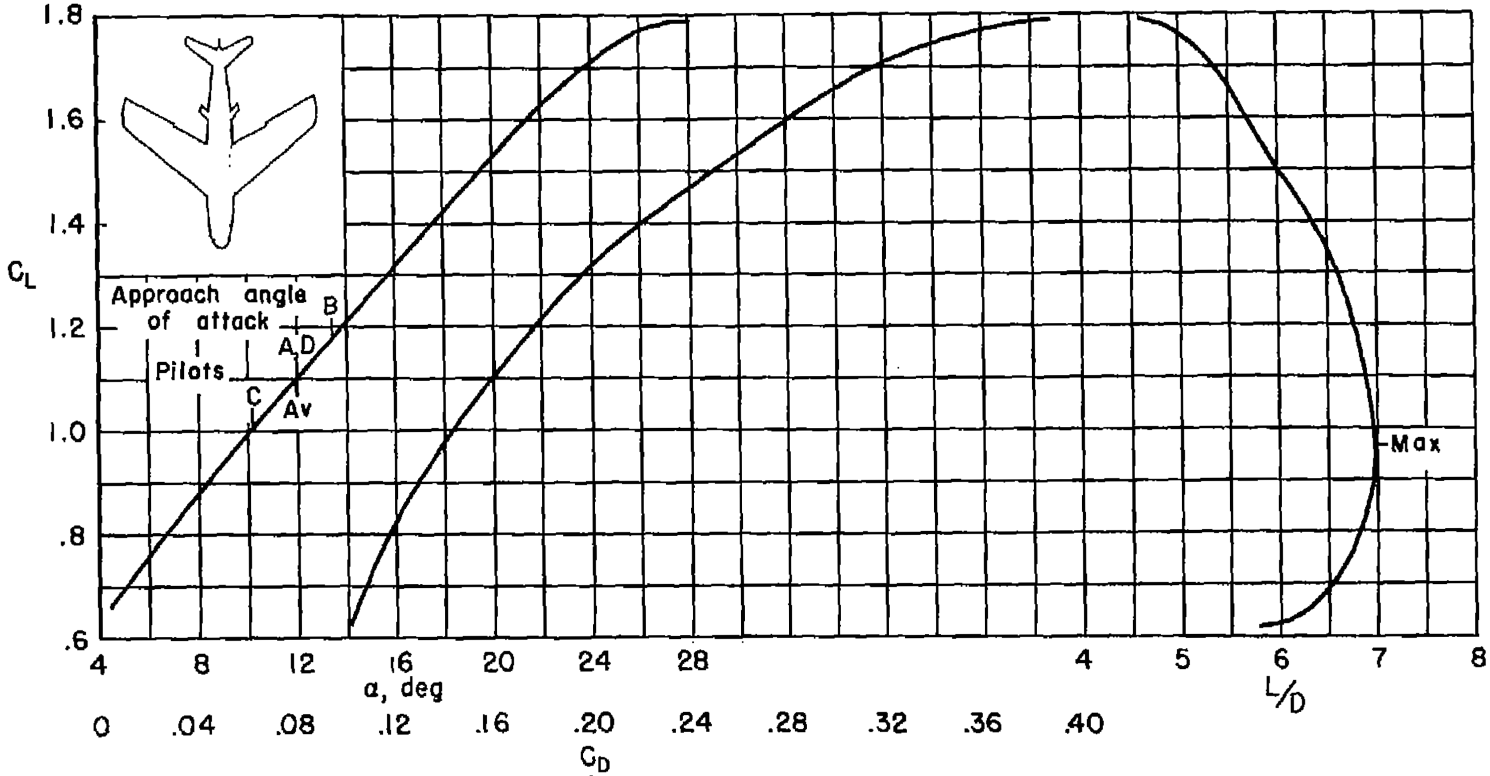
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 28.- Concluded.

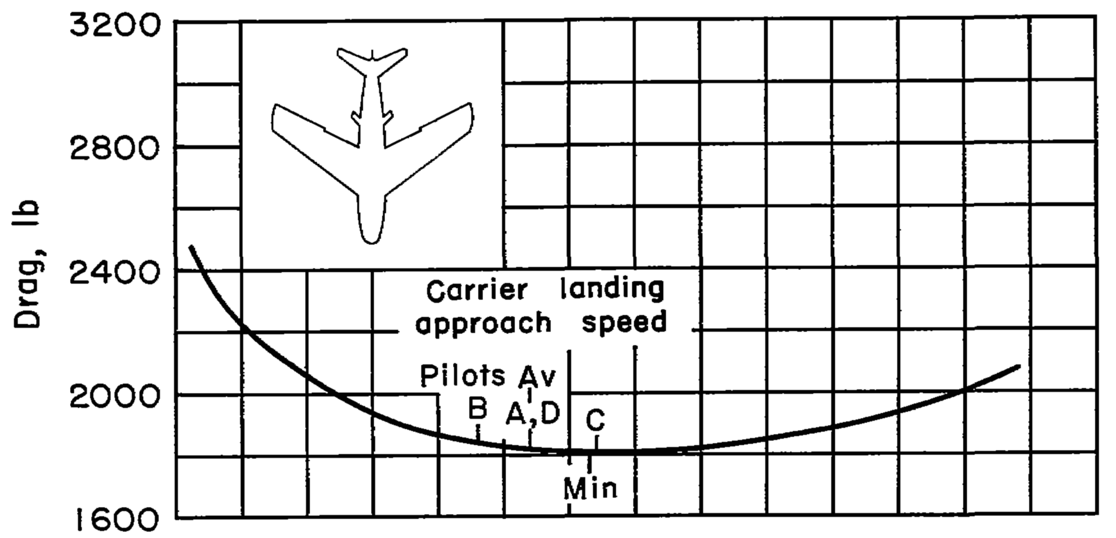
[redacted]



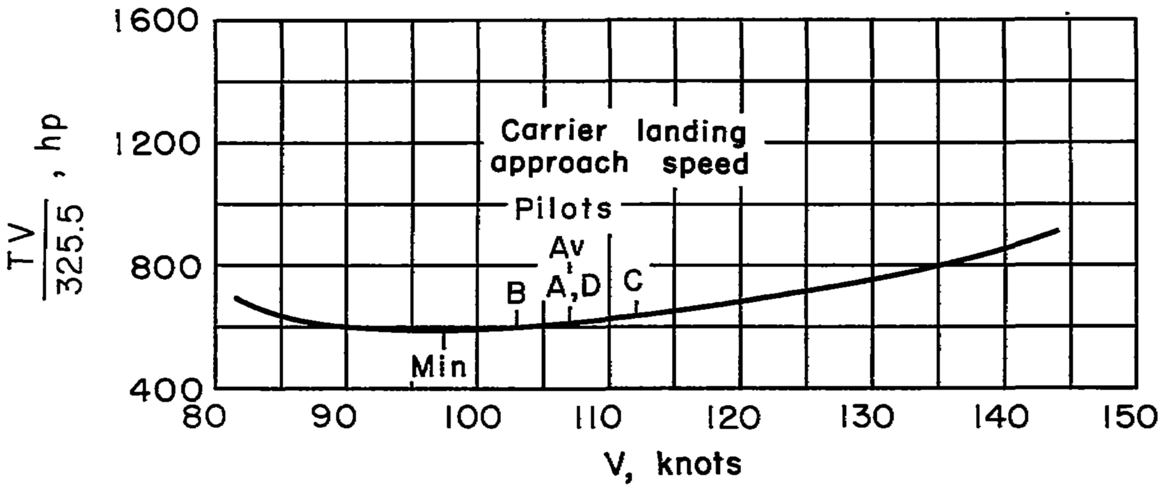
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 29.- Aerodynamic characteristics of the F-86F airplane; slotted flap, $\delta_f = 38^{\circ}$, suction leading-edge BLC (config. 12a).

[redacted]

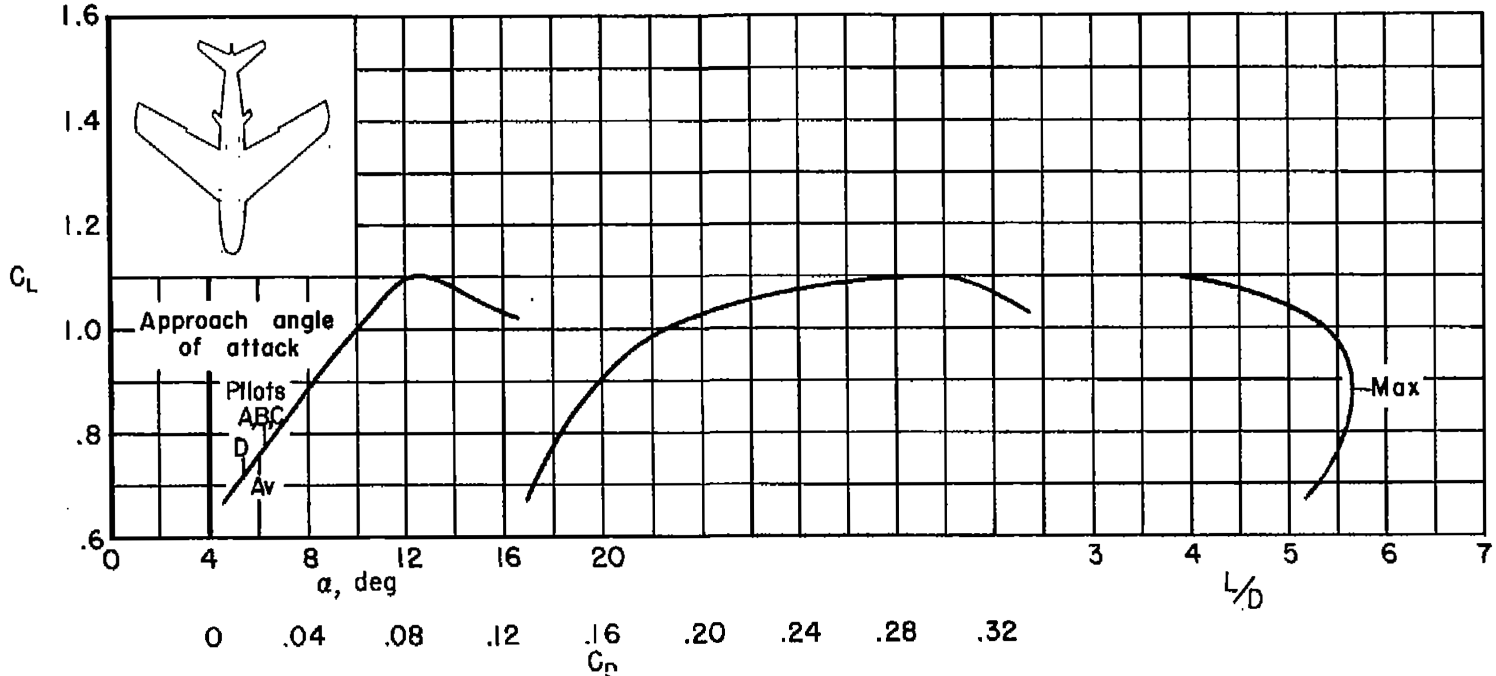


(b) Variation of airplane drag with velocity.



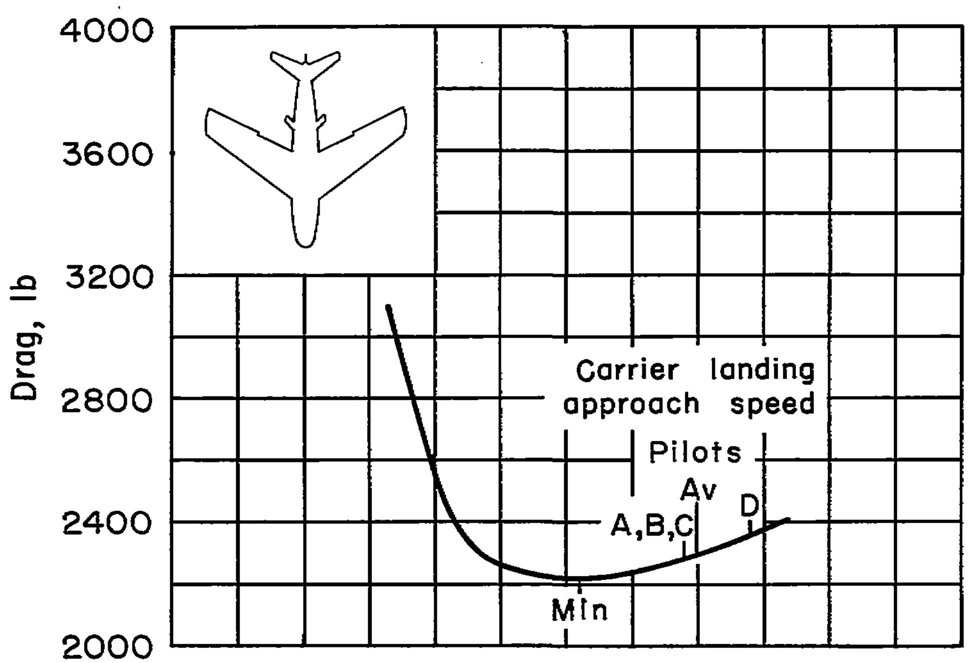
(c) Variation of horsepower required for level flight with velocity.

Figure 29.- Concluded.

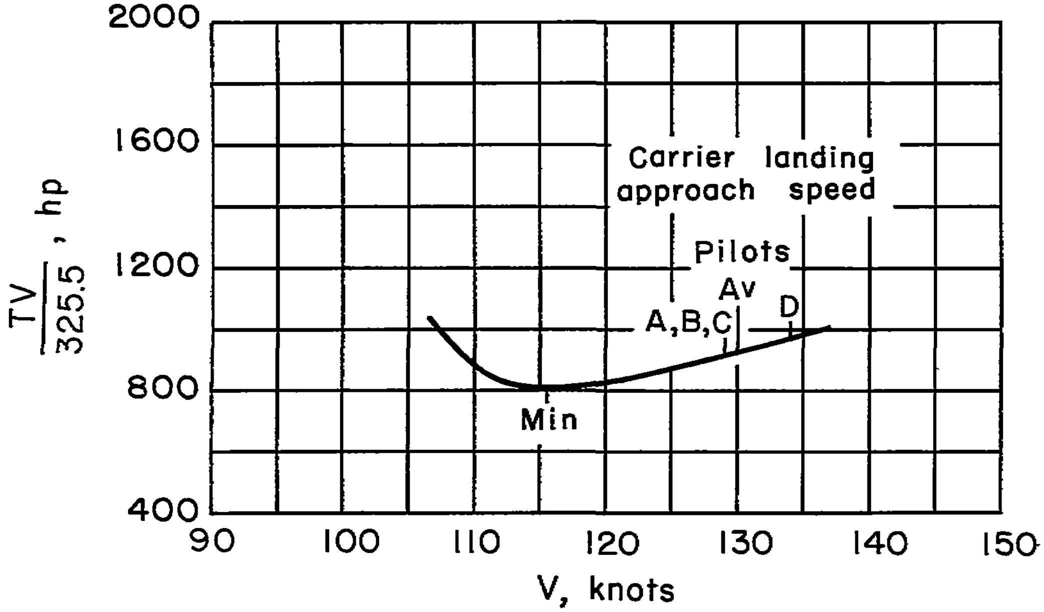


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 30.- Aerodynamic characteristics of the F-86F airplane; slotted flap, $\delta_f = 38^\circ$ (config. 12b).



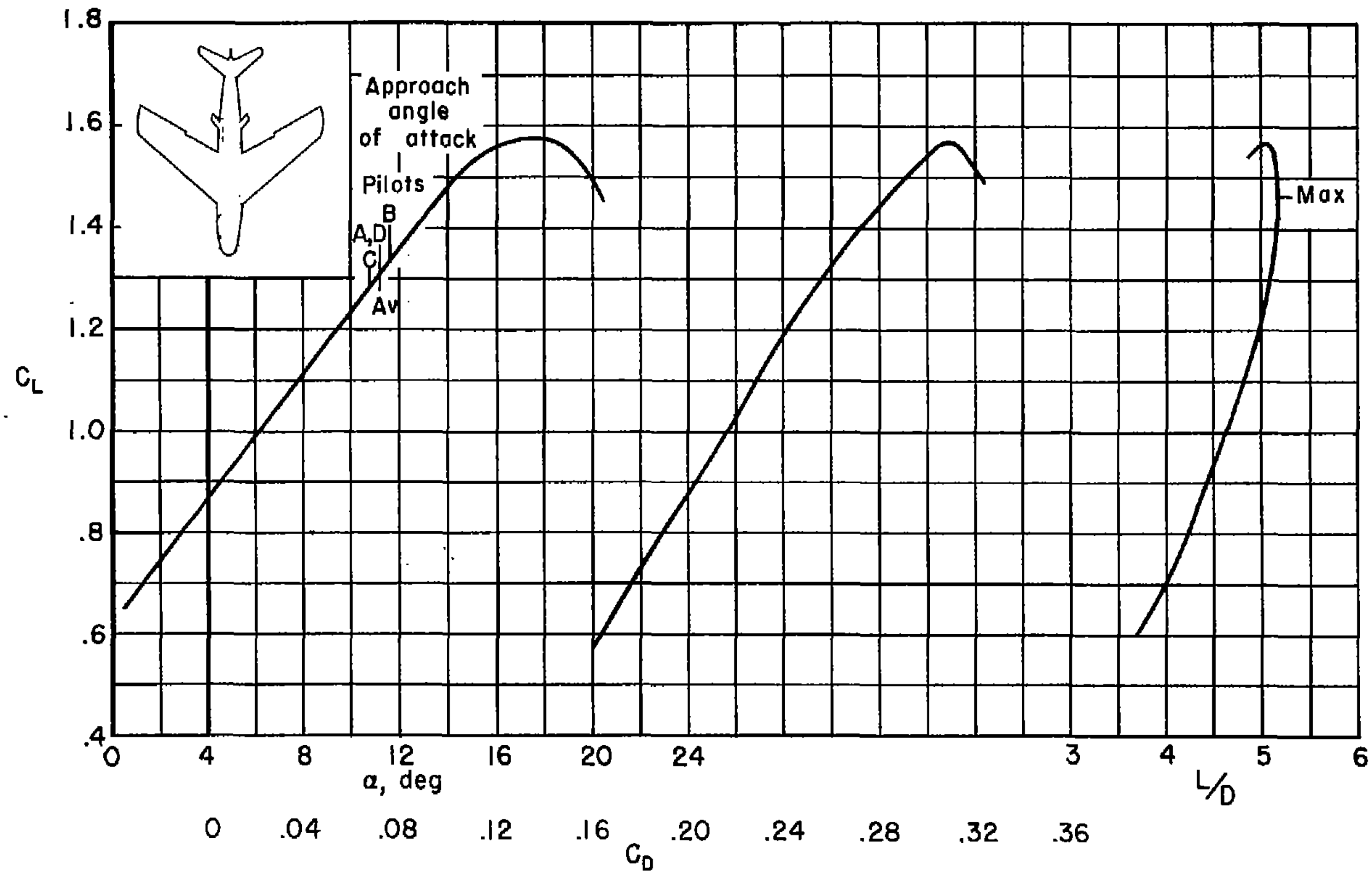
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

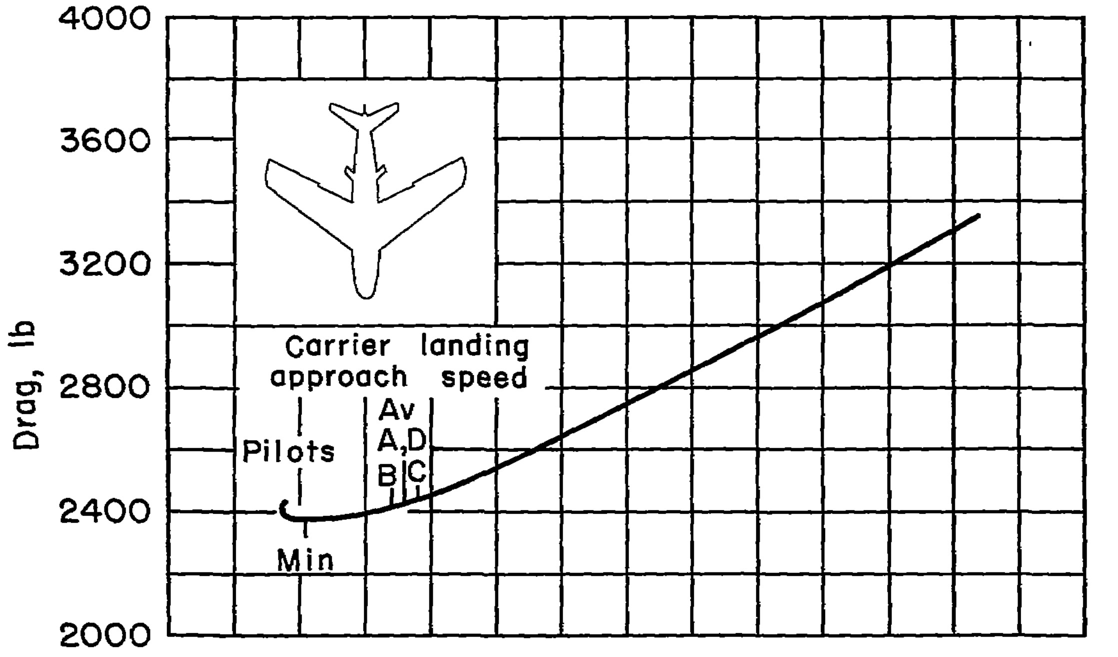
Figure 30.- Concluded.

[redacted]

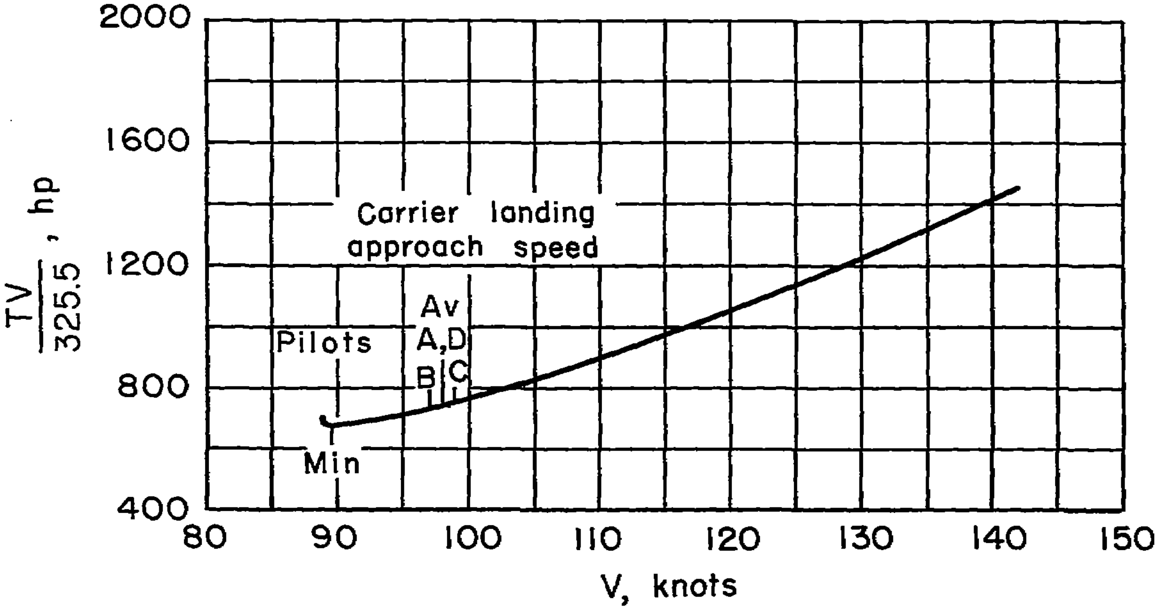


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 31.- Aerodynamic characteristics of the F-86F airplane; plain flap, $\delta_f = 55^{\circ}$, leading-edge slats, blowing-flap BLC (config. 13a).



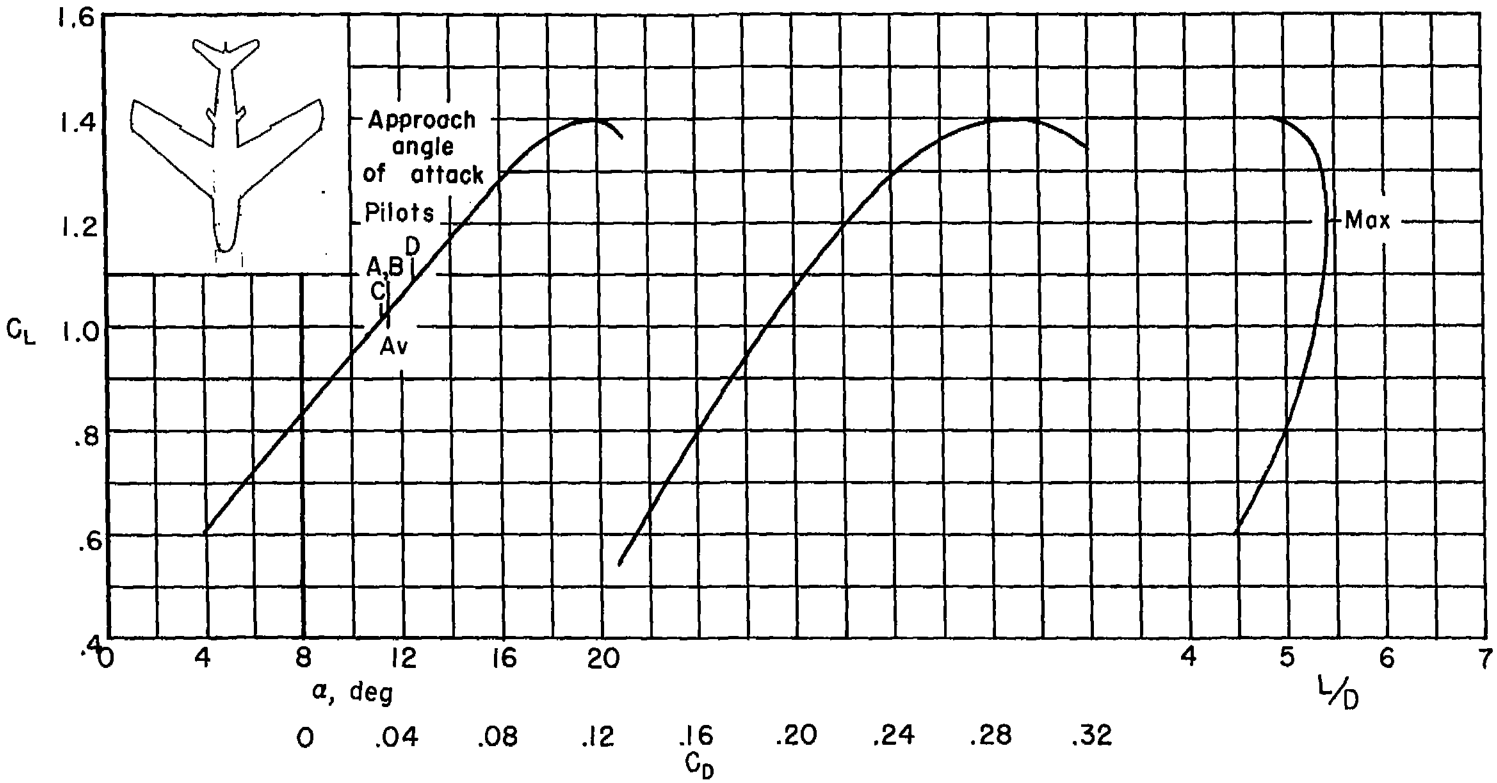
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 31.- Concluded.

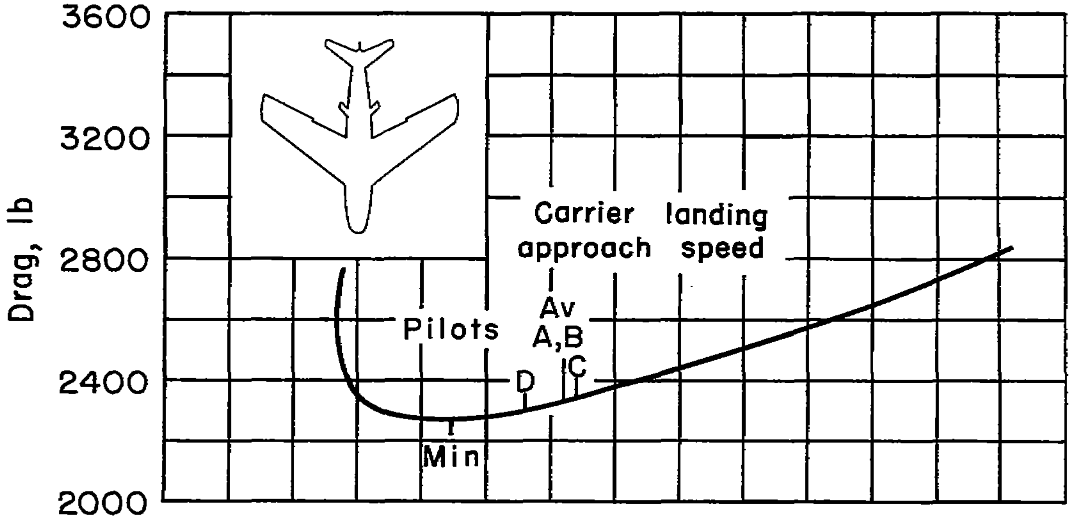
[redacted]



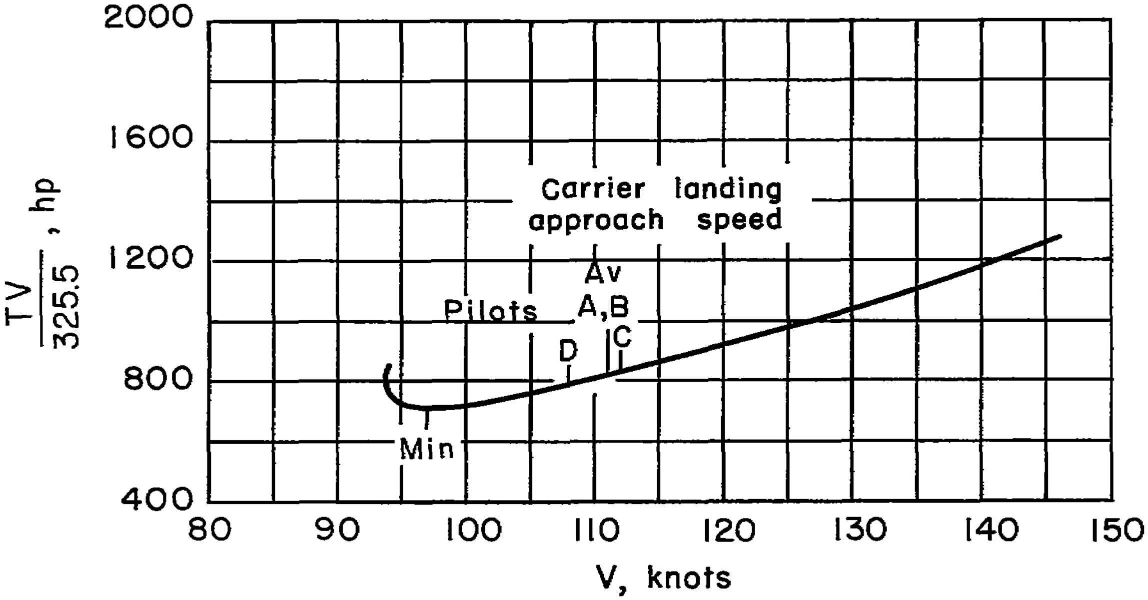
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 32.- Aerodynamic characteristics of the F-86F airplane; plain flap, $\delta_f = 55^\circ$, leading-edge slats (config. 13b).

[redacted]

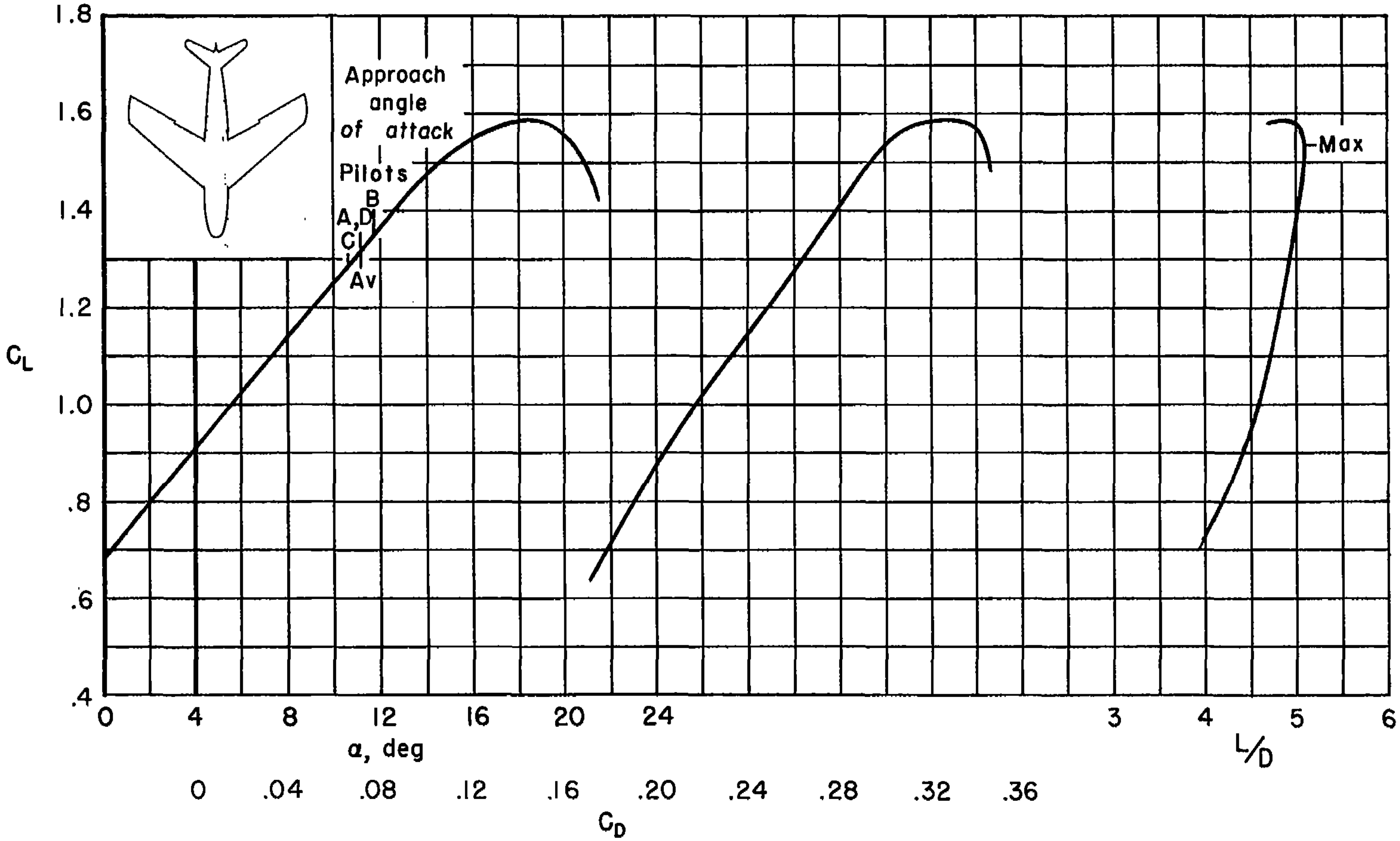


(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

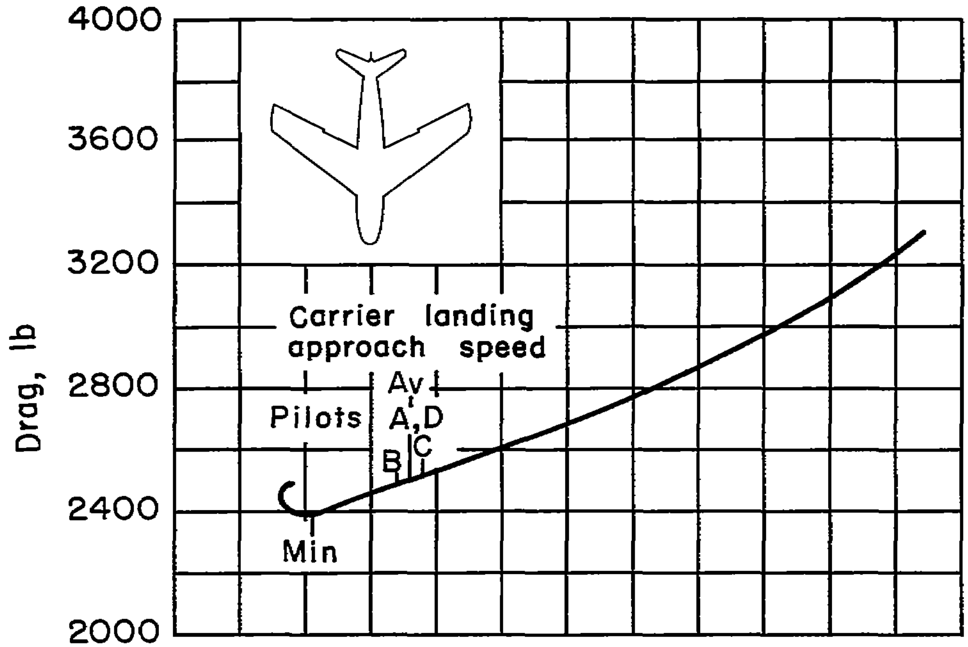
Figure 32.- Concluded.



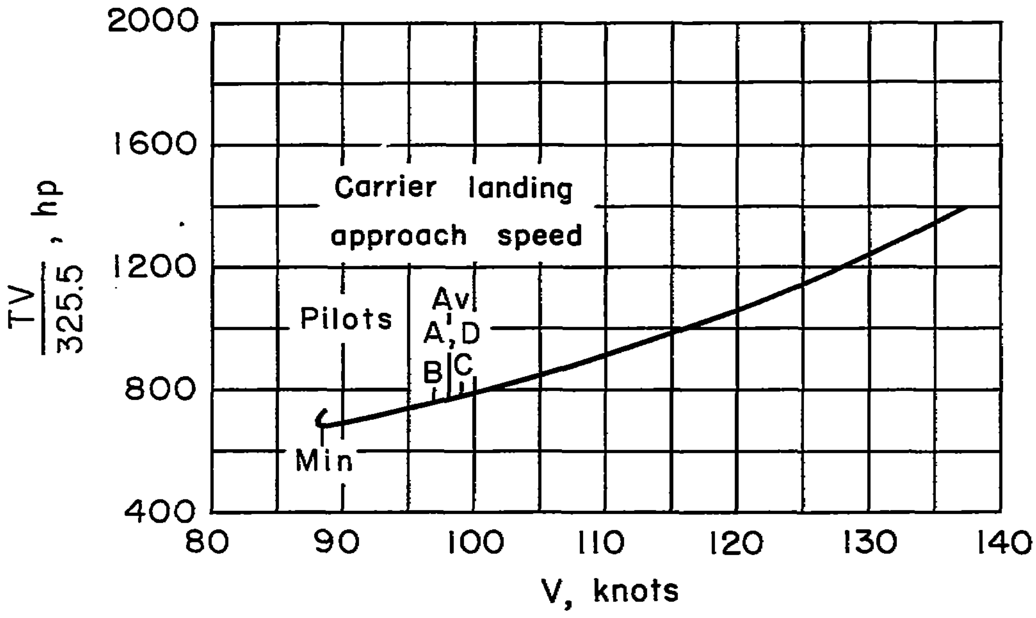
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 33.- Aerodynamic characteristics of the F-86F airplane; plain flap, $\delta_f = 66^\circ$, leading-edge slats, blowing-flap BLC (config. 13c).

[redacted]

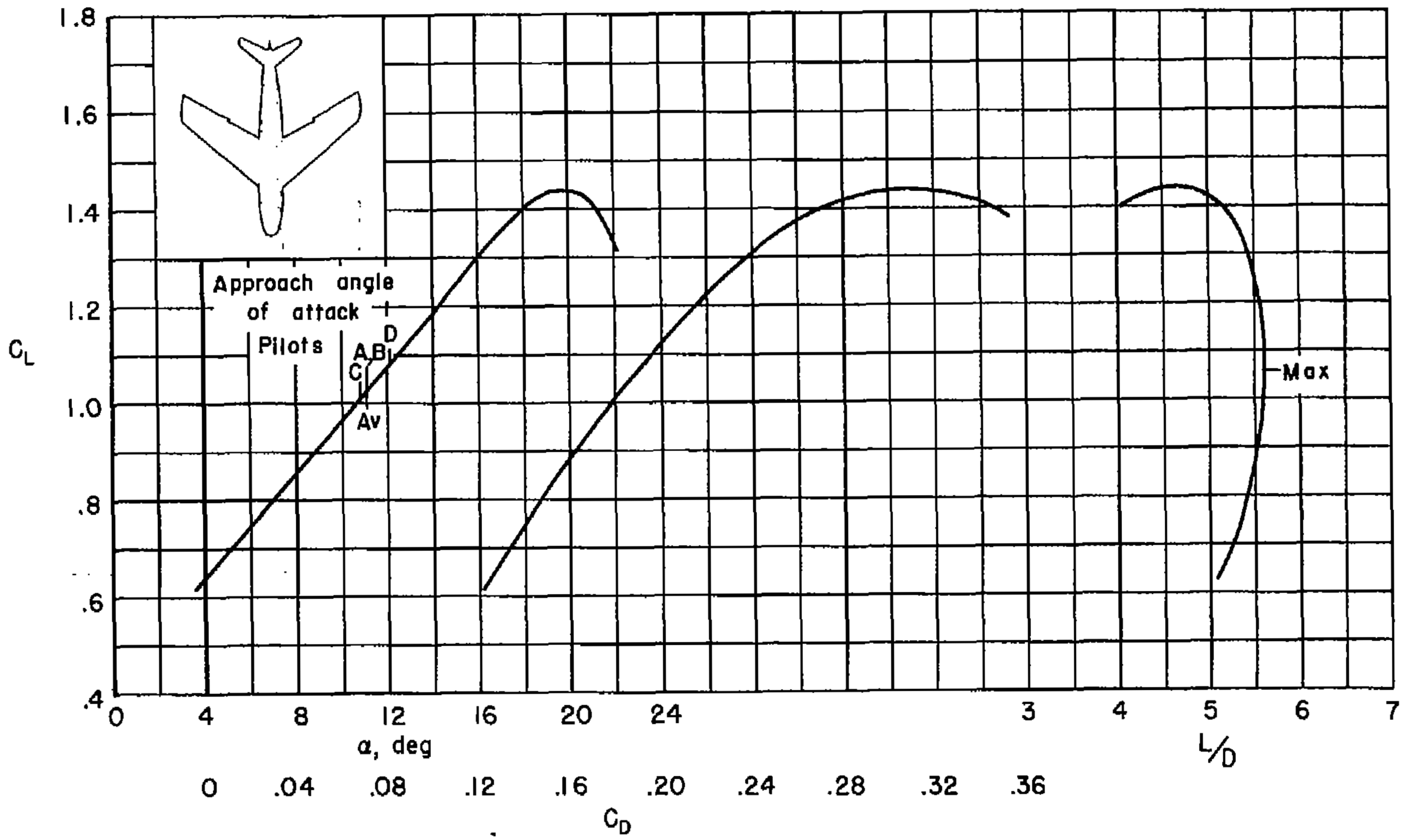


(b) Variation of airplane drag with velocity.



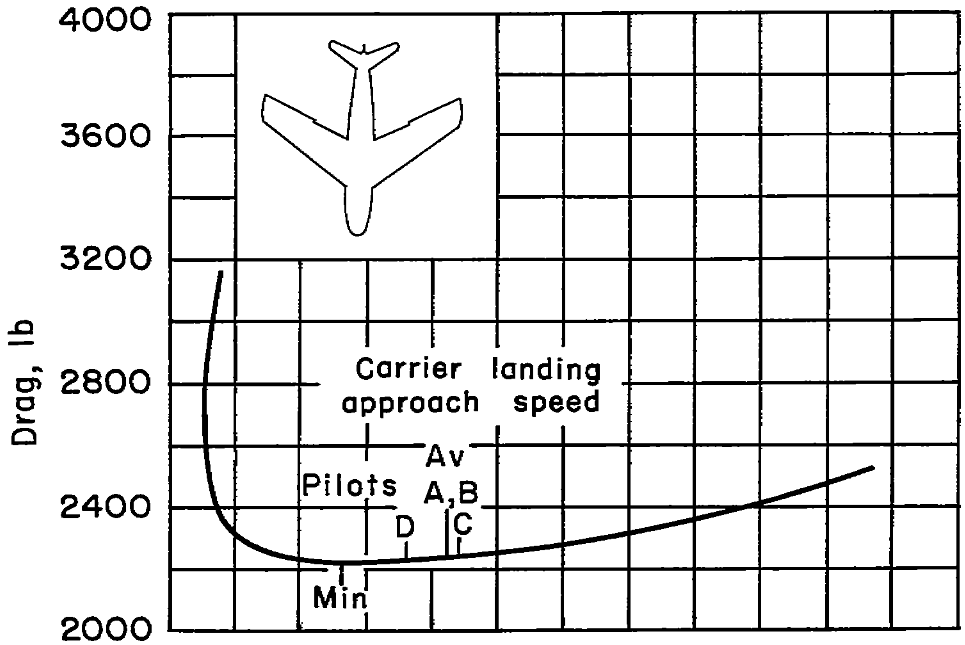
(c) Variation of horsepower required for level flight with velocity.

Figure 33.- Concluded.

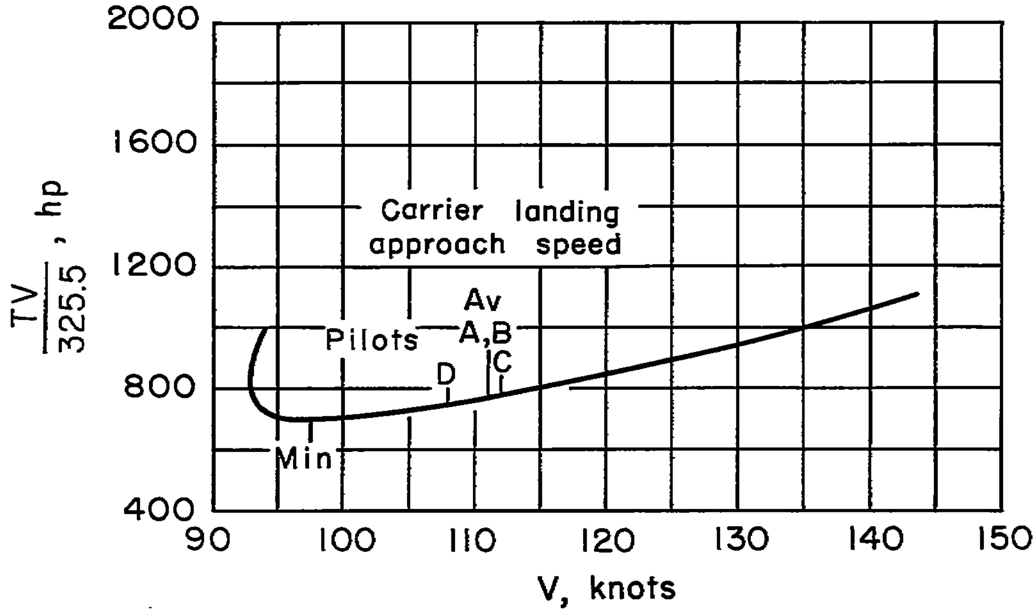


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 34.- Aerodynamic characteristics of the F-86F airplane; plain flap, $\delta_f = 66^{\circ}$, leading-edge slats (config. 13d).

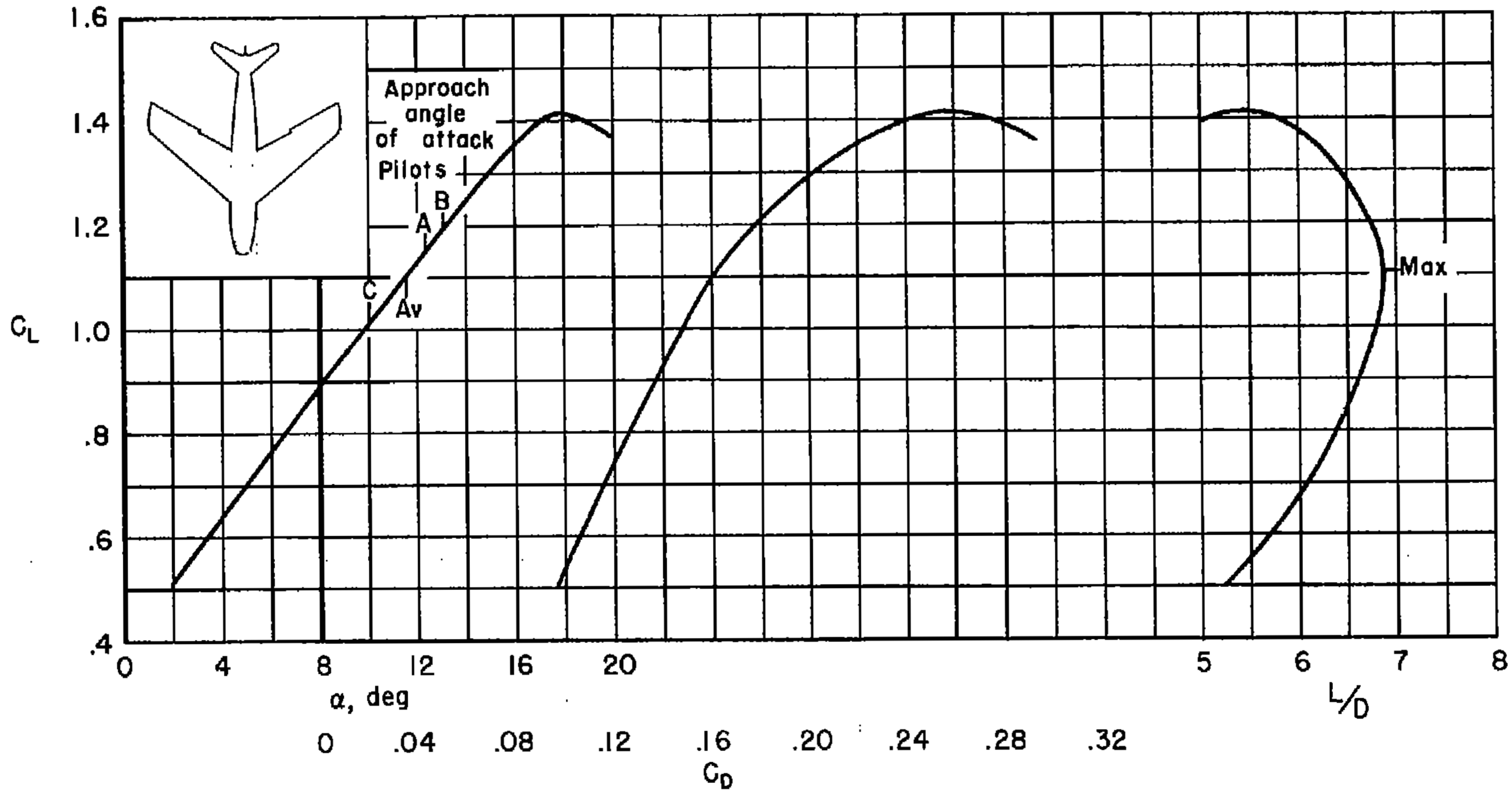


(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

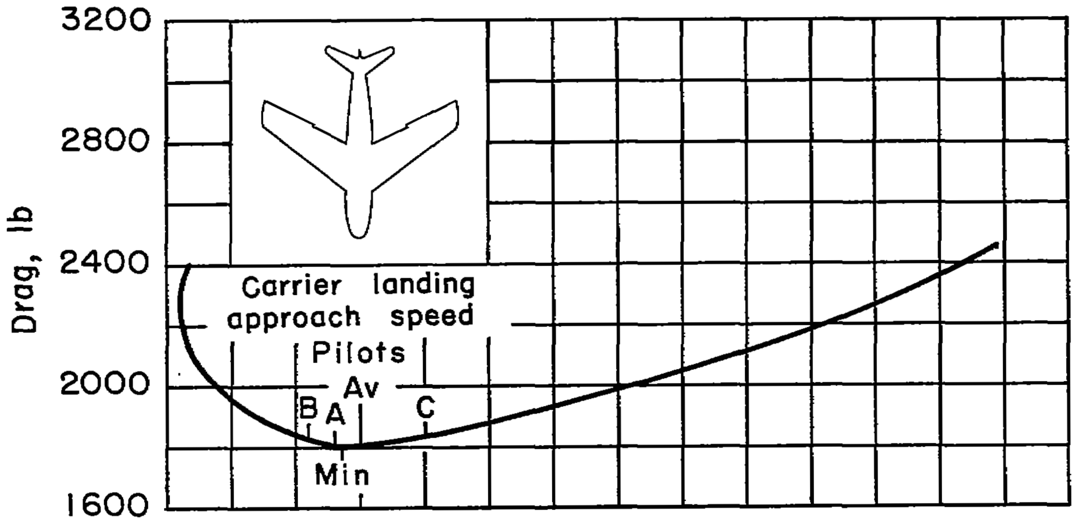
Figure 34.- Concluded.



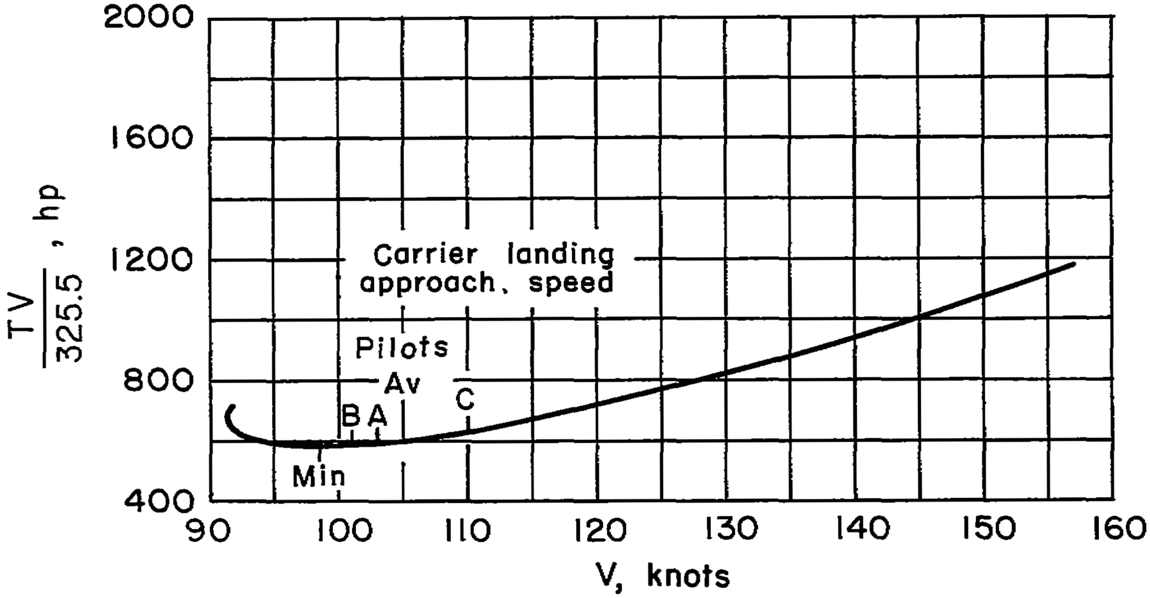
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 35.- Aerodynamic characteristics of the F-86F airplane; plain flap, $\delta_f = 55^{\circ}$, 6-3 slatted leading edge (config. 14a).

[redacted]

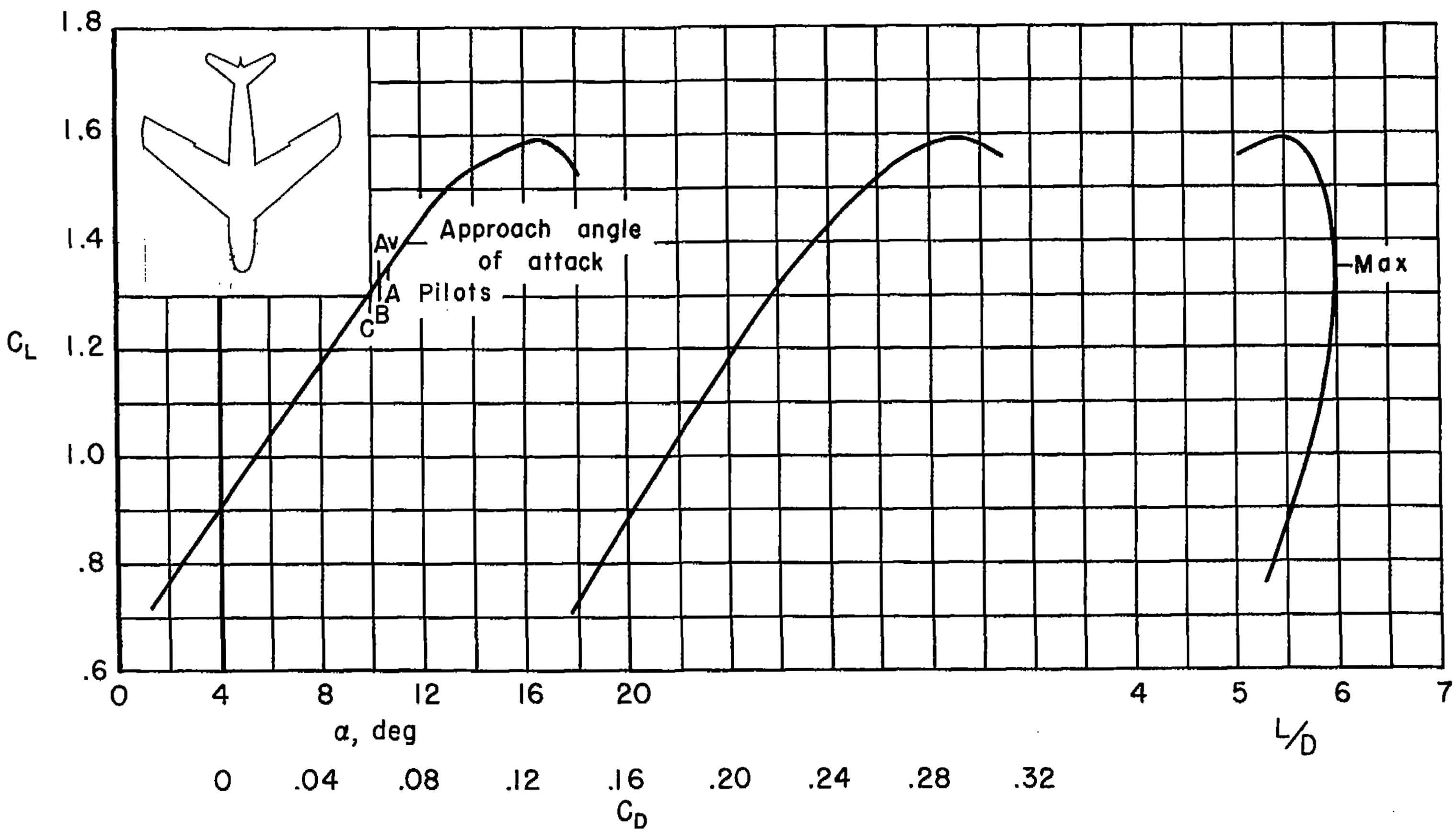


(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

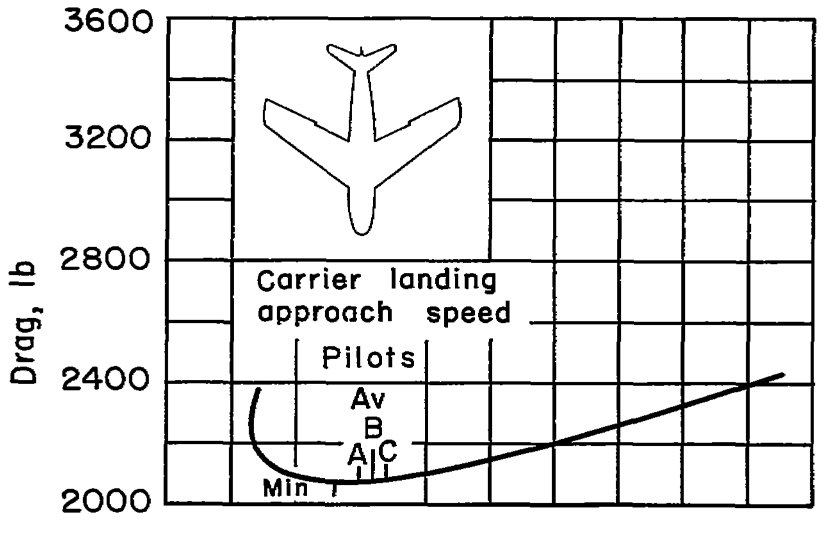
Figure 35.- Concluded.



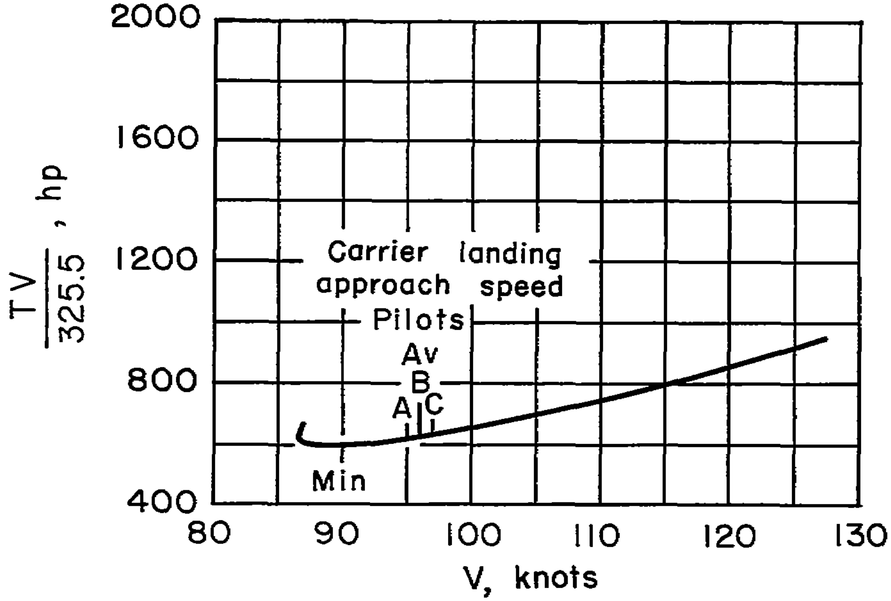
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 36.- Aerodynamic characteristics of the F-86F airplane; plain flap, $\delta_f = 55^{\circ}$, 6-3 slatted leading edge, blowing-flap BLC (config. 14b).

[redacted]



(b) Variation of airplane drag with velocity.

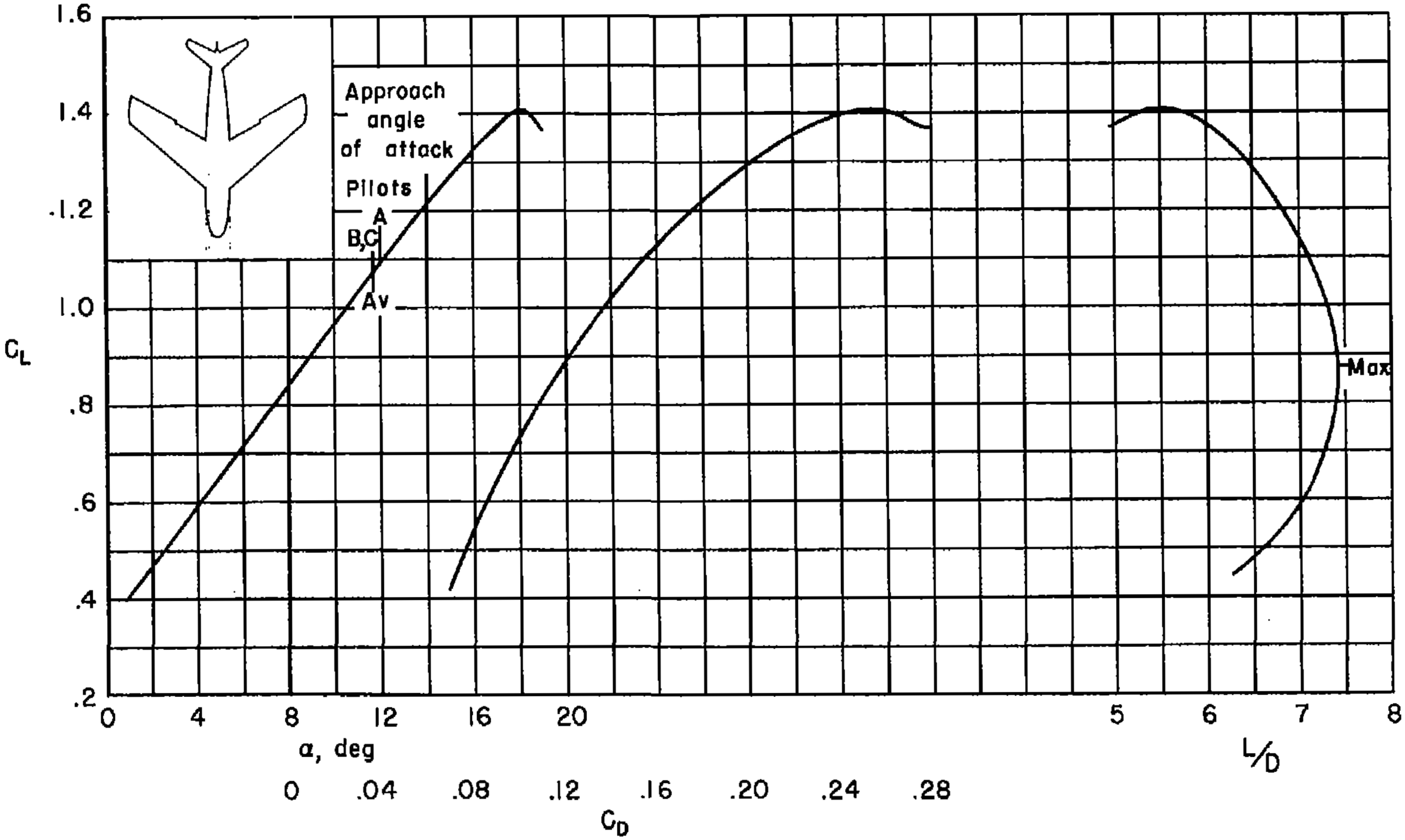


(c) Variation of horsepower required for level flight with velocity.

Figure 36.- Concluded.

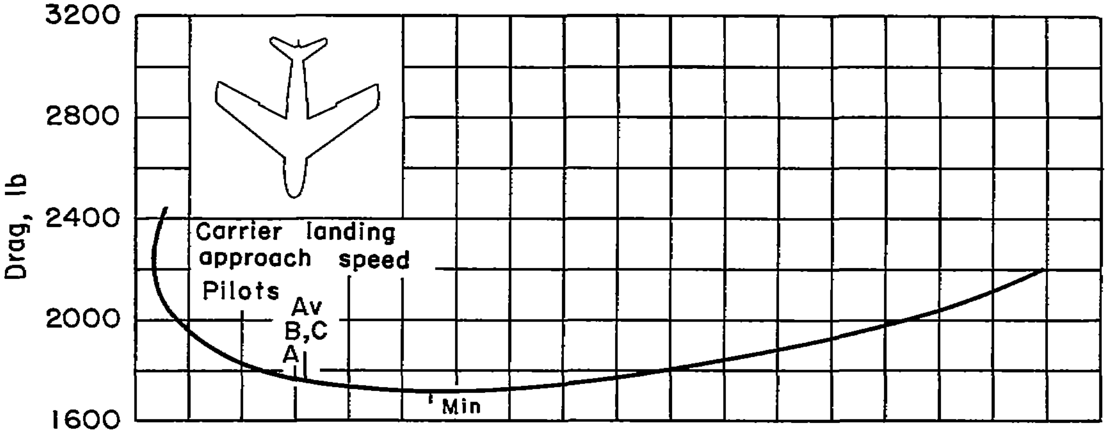
[redacted]

[redacted]

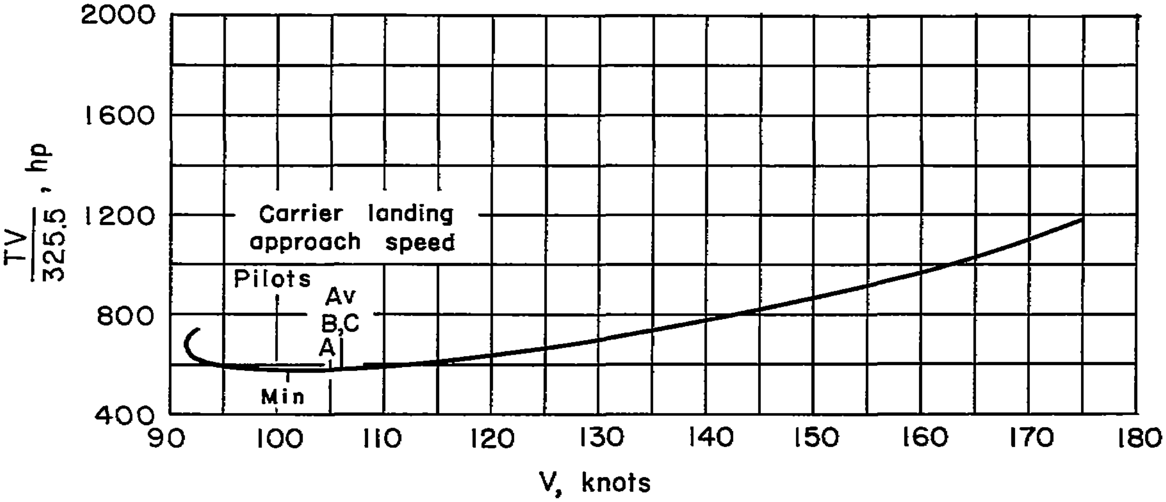


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 37.- Aerodynamic characteristics of the F-86F airplane; slotted flap, $\delta_f = 38^{\circ}$, 6-3 slatted leading edge (config. 14c).



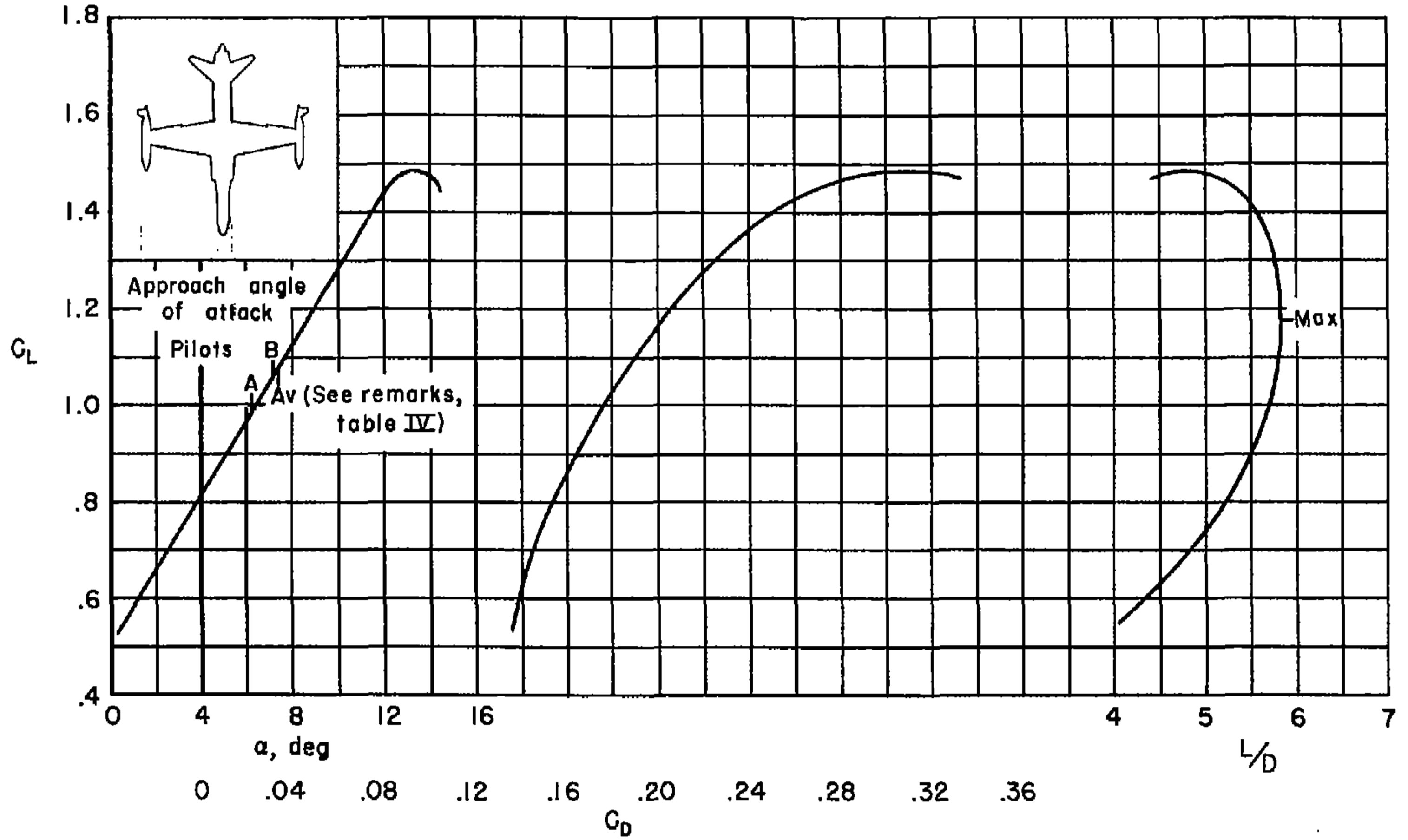
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

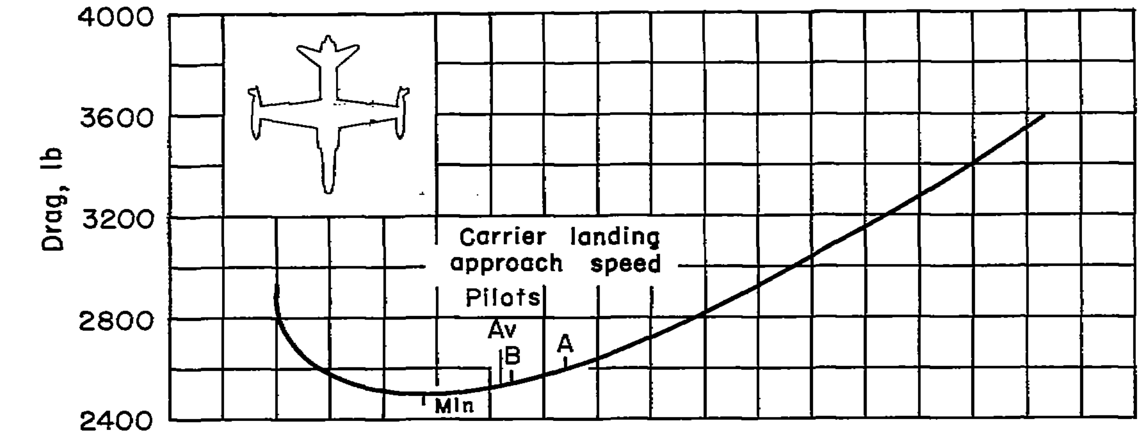
Figure 37.- Concluded.

[redacted]

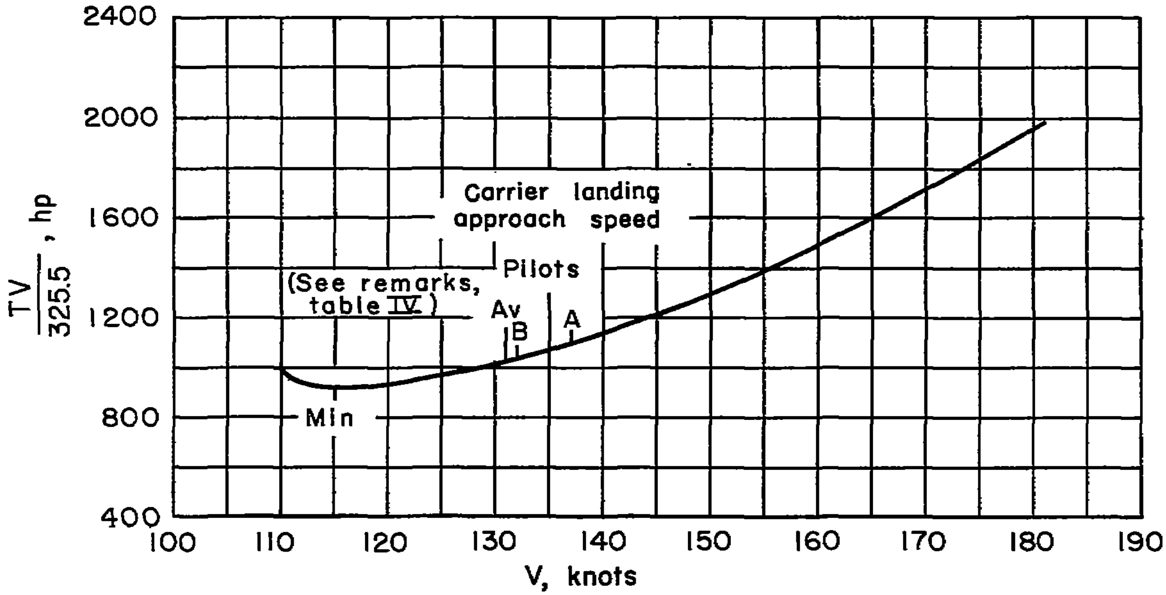


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 38.- Aerodynamic characteristics of the F-94C airplane; split flap, $\delta_f = 45^{\circ}$ (config. 15a).



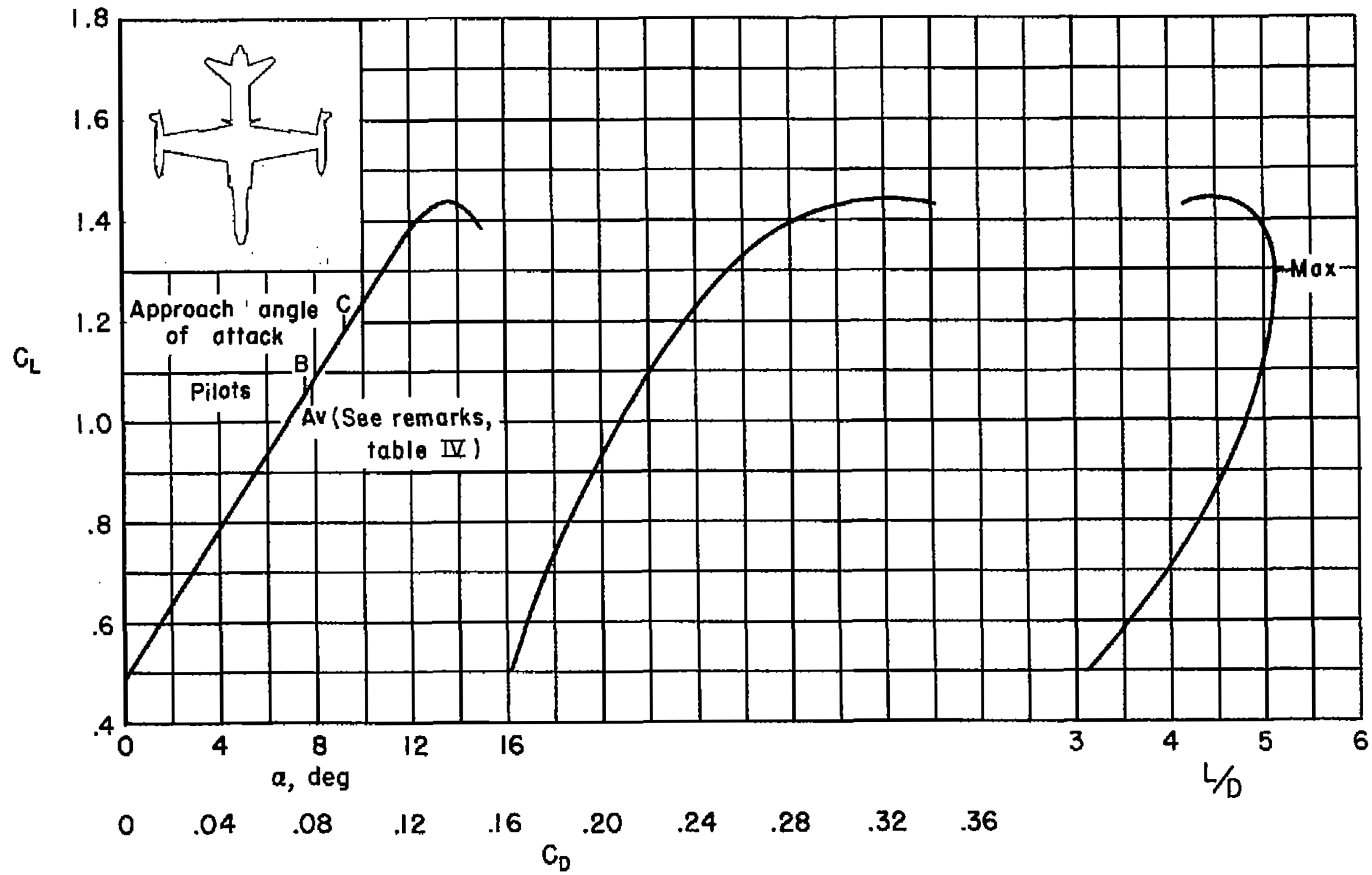
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 38.- Concluded.

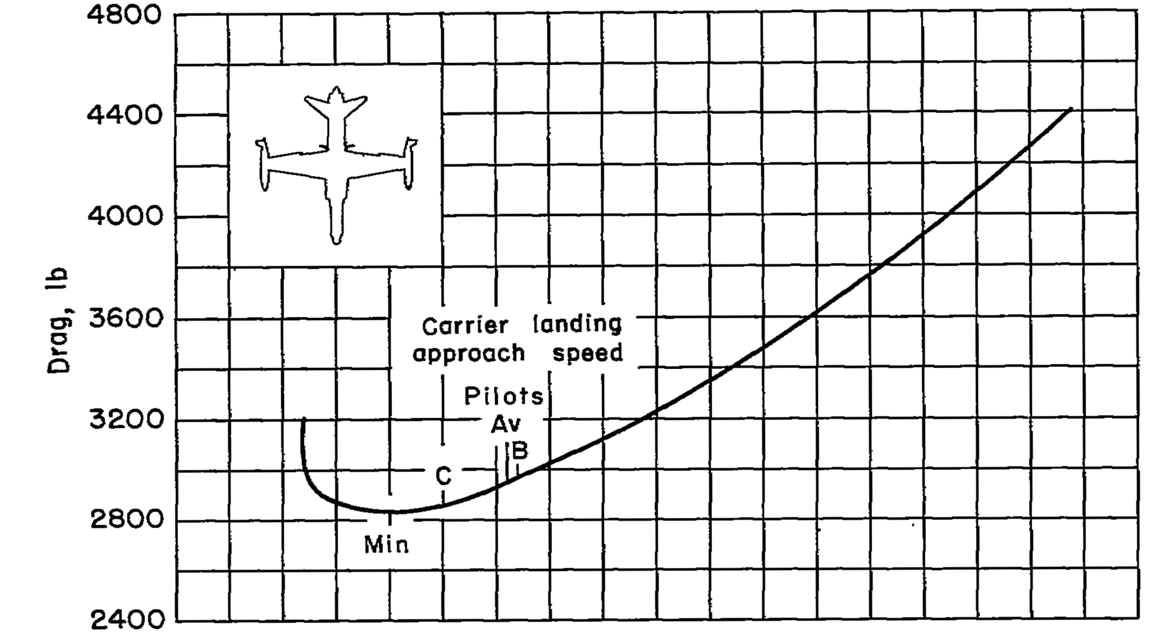
[redacted]



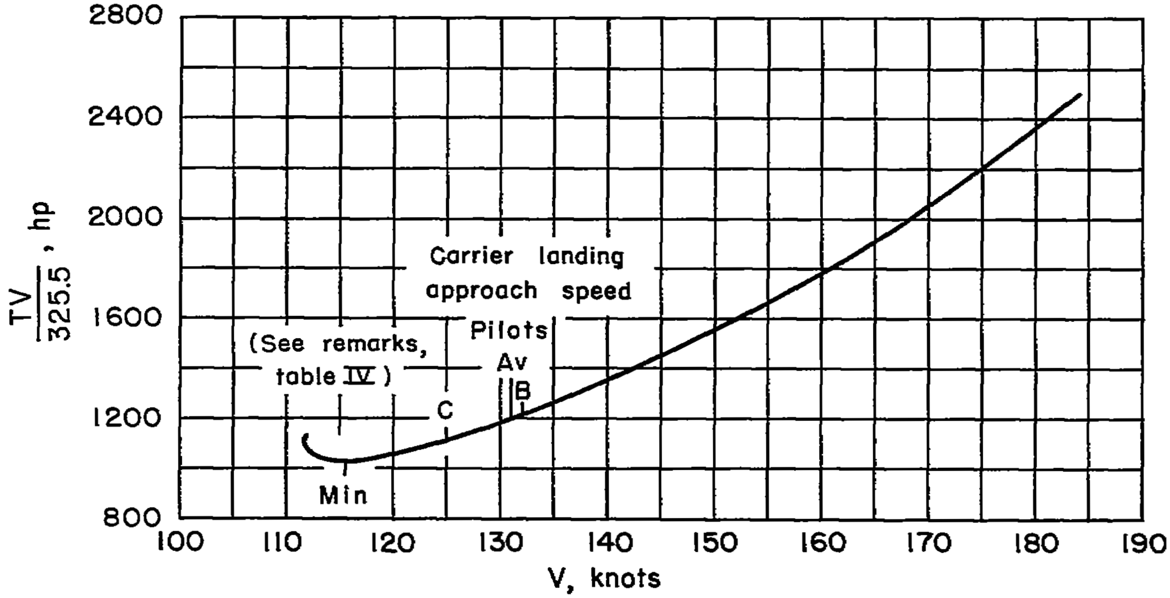
[redacted]

(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 39.- Aerodynamic characteristics of the F-94C airplane; split flap, $\delta_f = 45^{\circ}$, speed brakes (config. 15b).



(b) Variation of airplane drag with velocity.

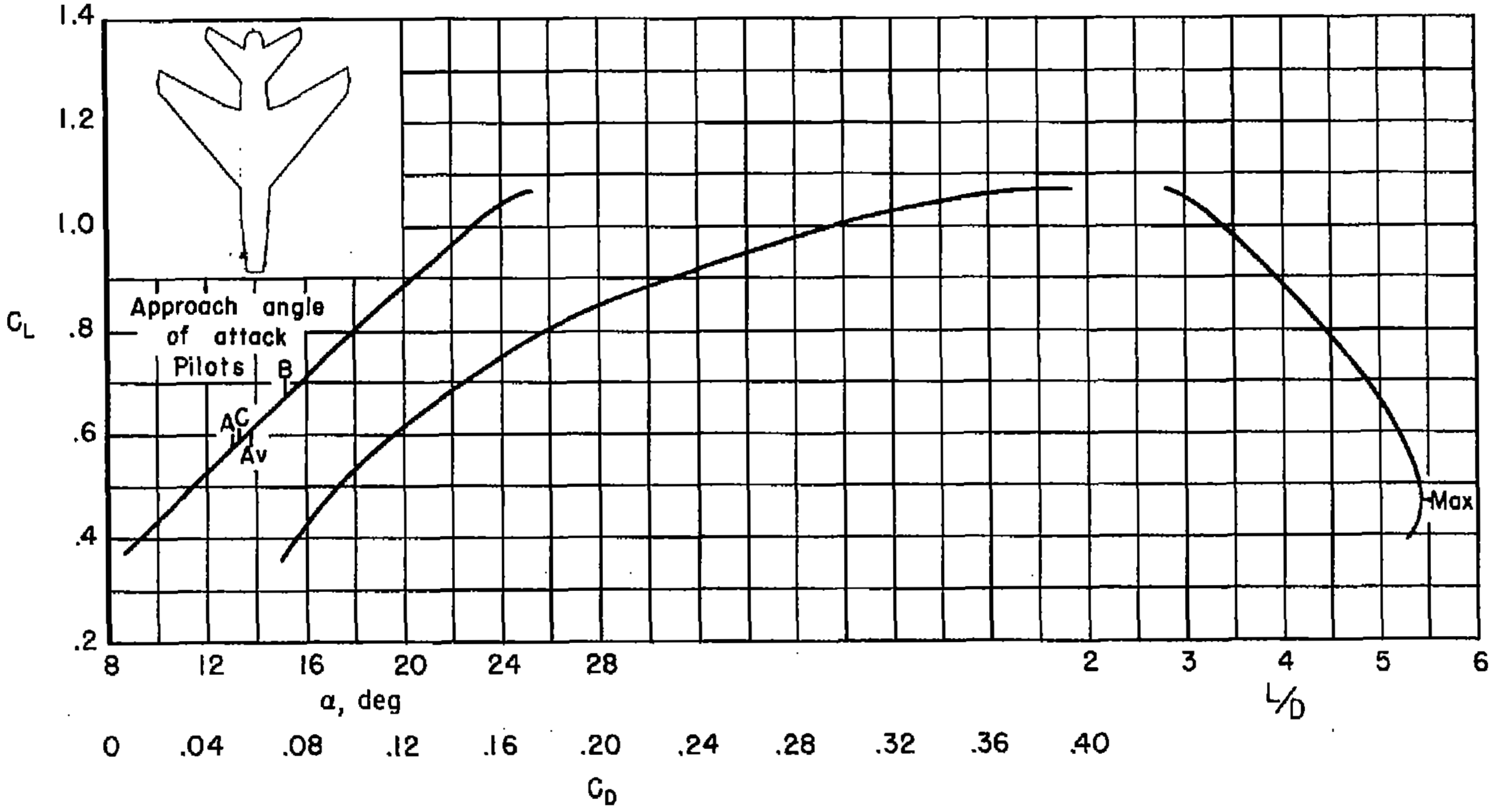


(c) Variation of horsepower required for level flight with velocity.

Figure 39.- Concluded.

[redacted]

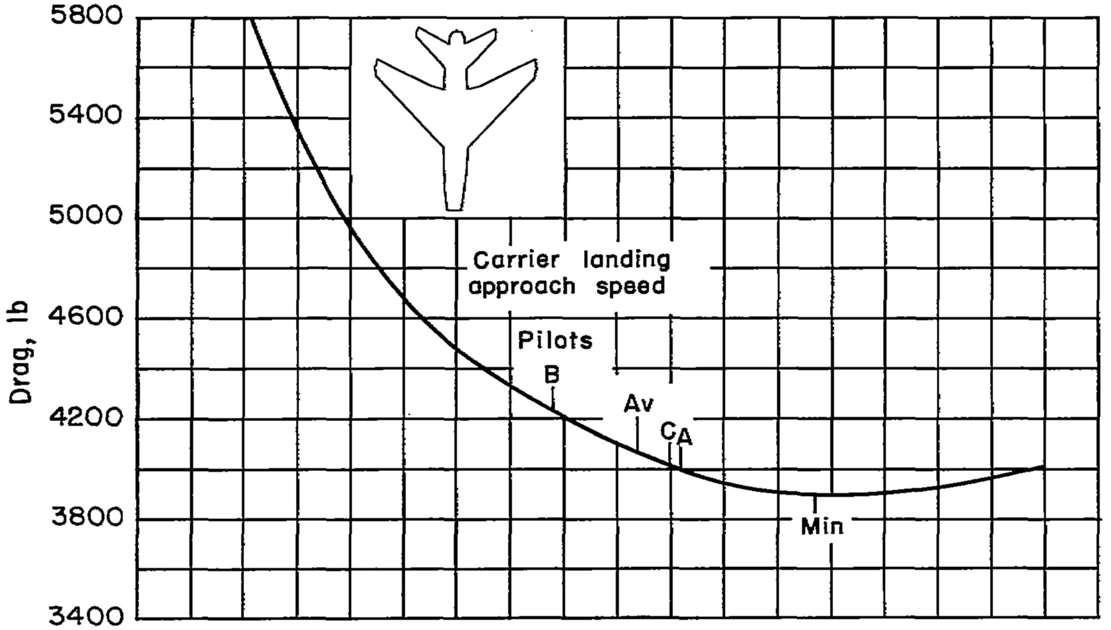
[redacted]



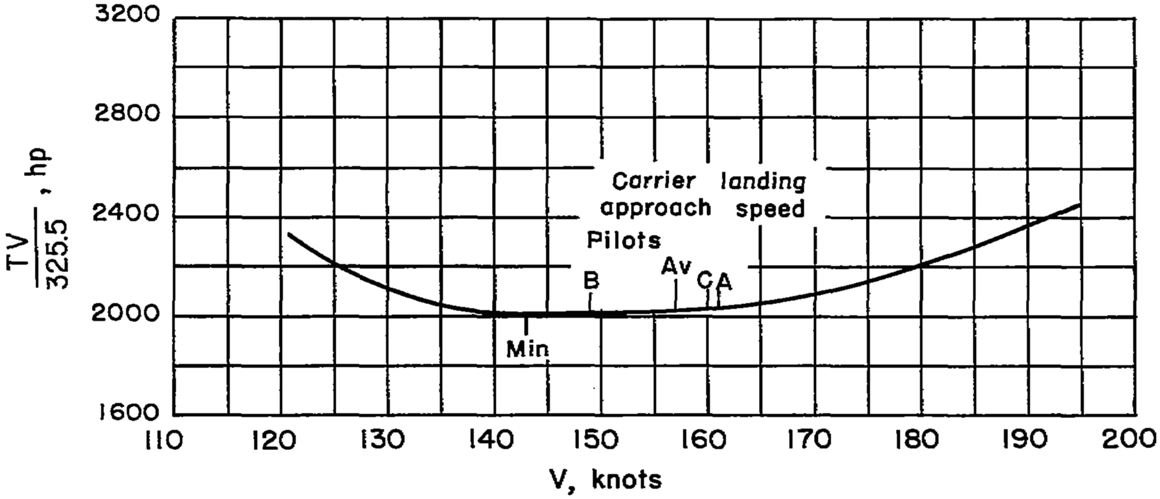
(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 40.- Aerodynamic characteristics of the F-100A airplane; leading-edge slats (config. 16a).

C[redacted]



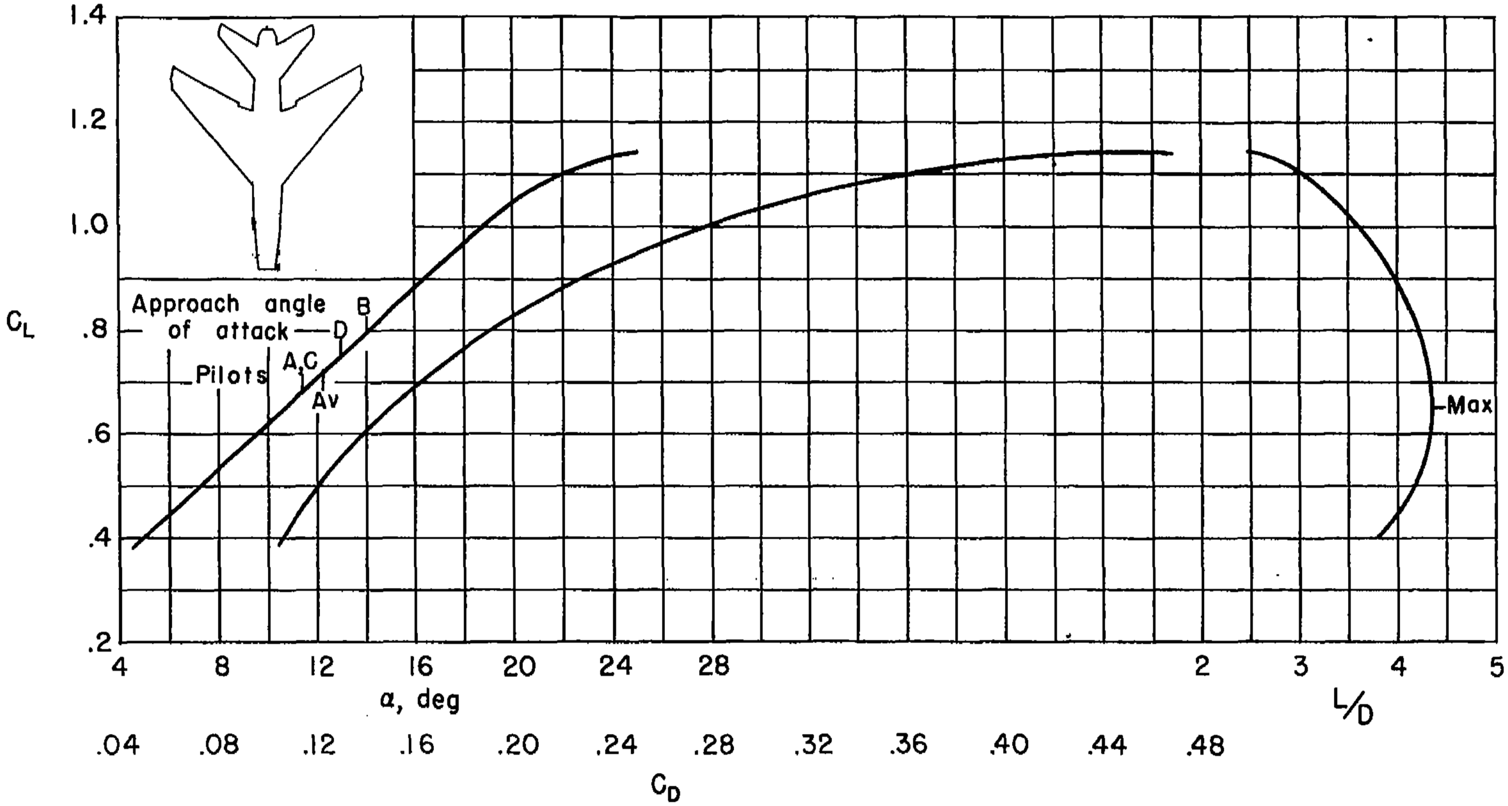
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 40.- Concluded.

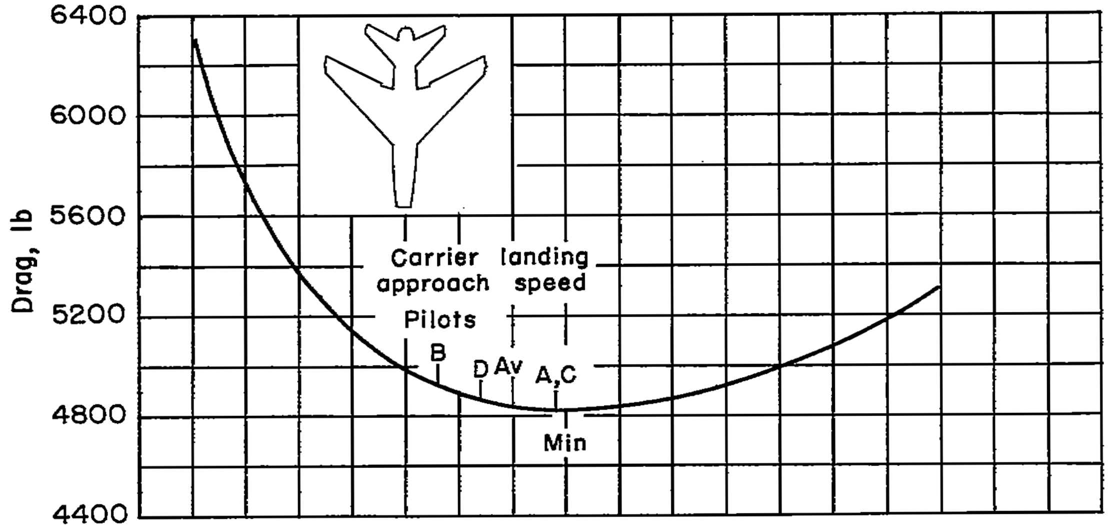
[redacted]



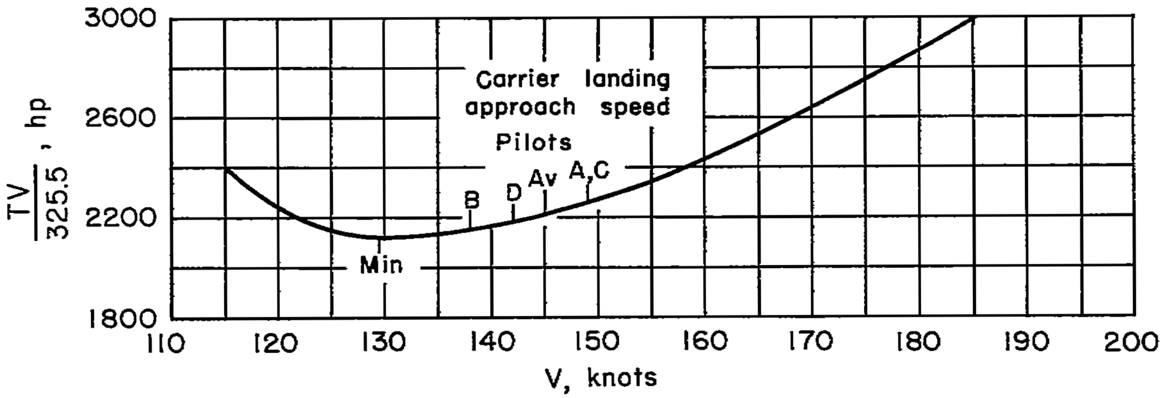
[redacted]

(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 41.- Aerodynamic characteristics of the F-100A airplane; plain flap, $\delta_f = 45^\circ$, leading-edge slats (config. 16b).



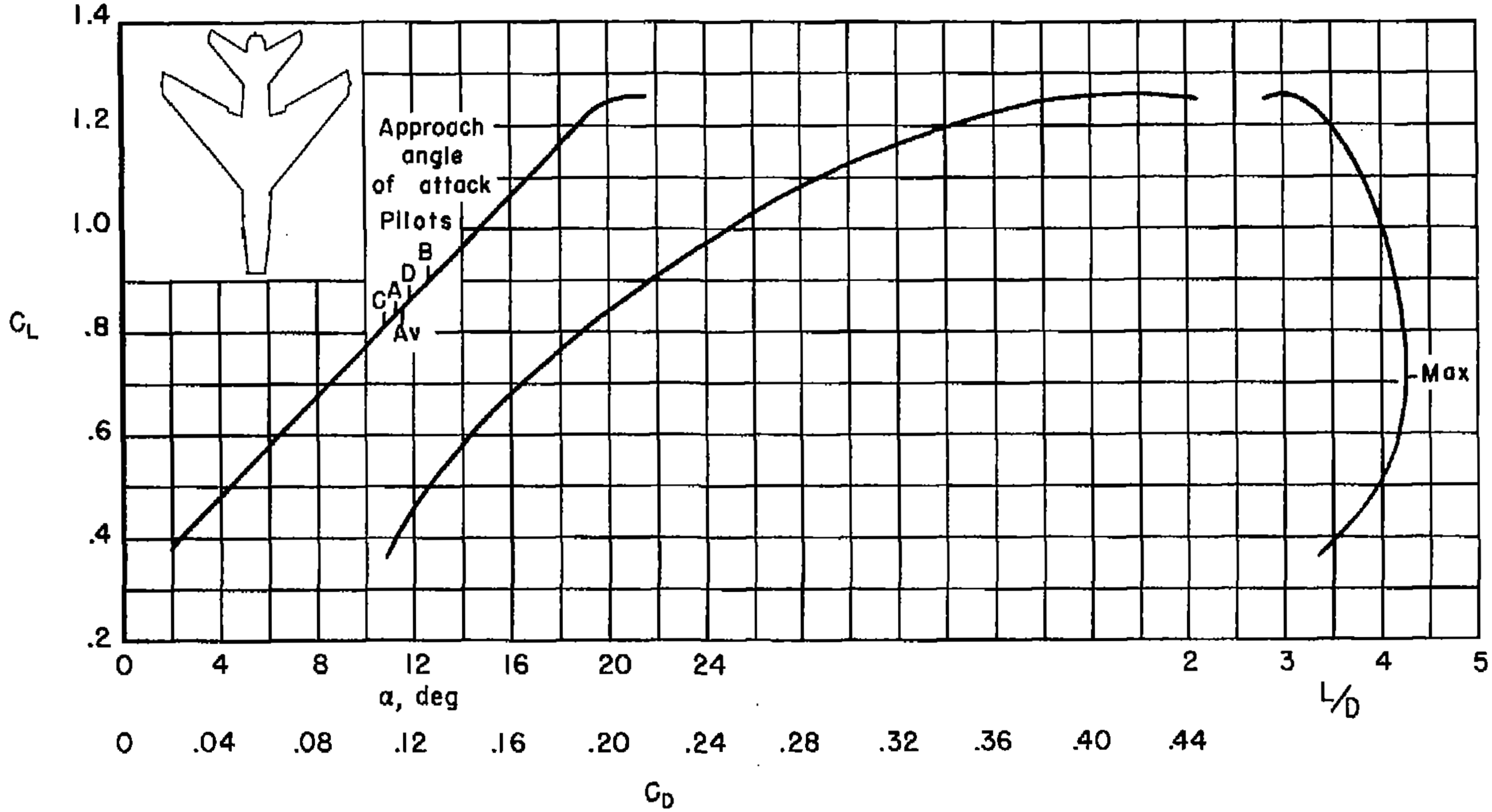
(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

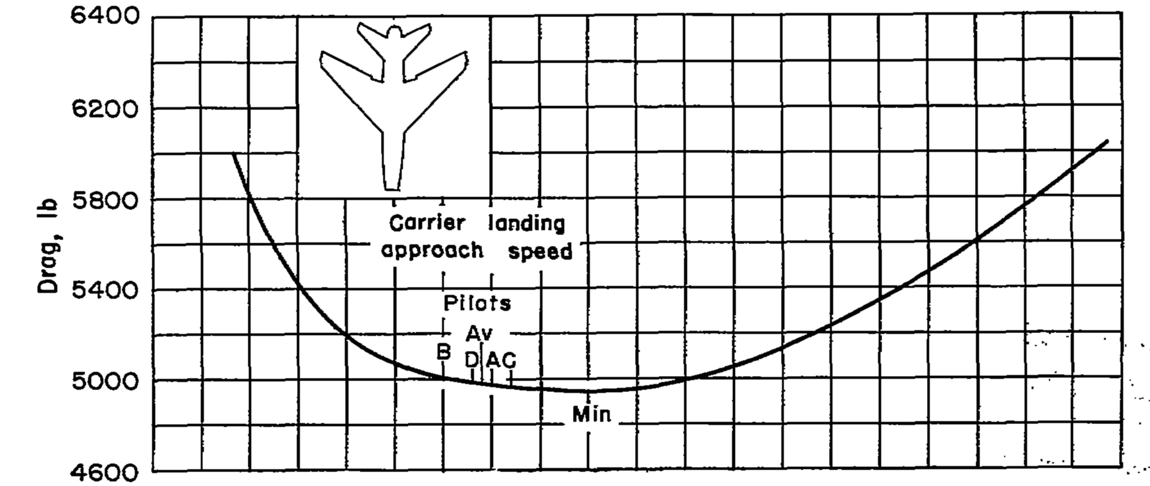
Figure 41.- Concluded.

[redacted]

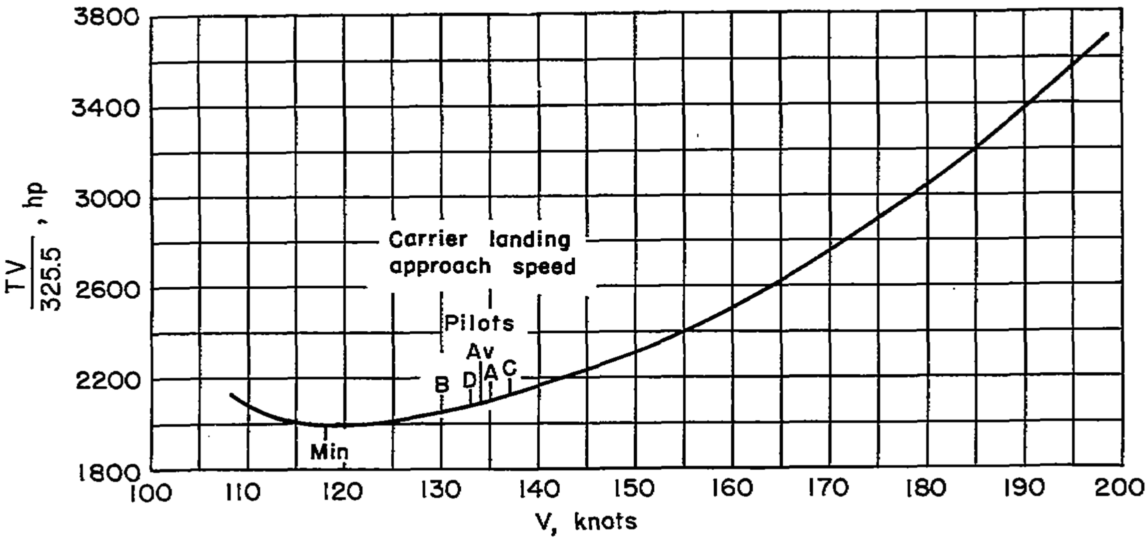


(a) Variation of lift coefficient with angle of attack, drag coefficient, and lift-drag ratio.

Figure 42.- Aerodynamic characteristics of the F-100A airplane; plain flap, $\delta_f = 45^\circ$, leading-edge slats, blowing-flap BLC (config. 16c).



(b) Variation of airplane drag with velocity.



(c) Variation of horsepower required for level flight with velocity.

Figure 42.- Concluded.

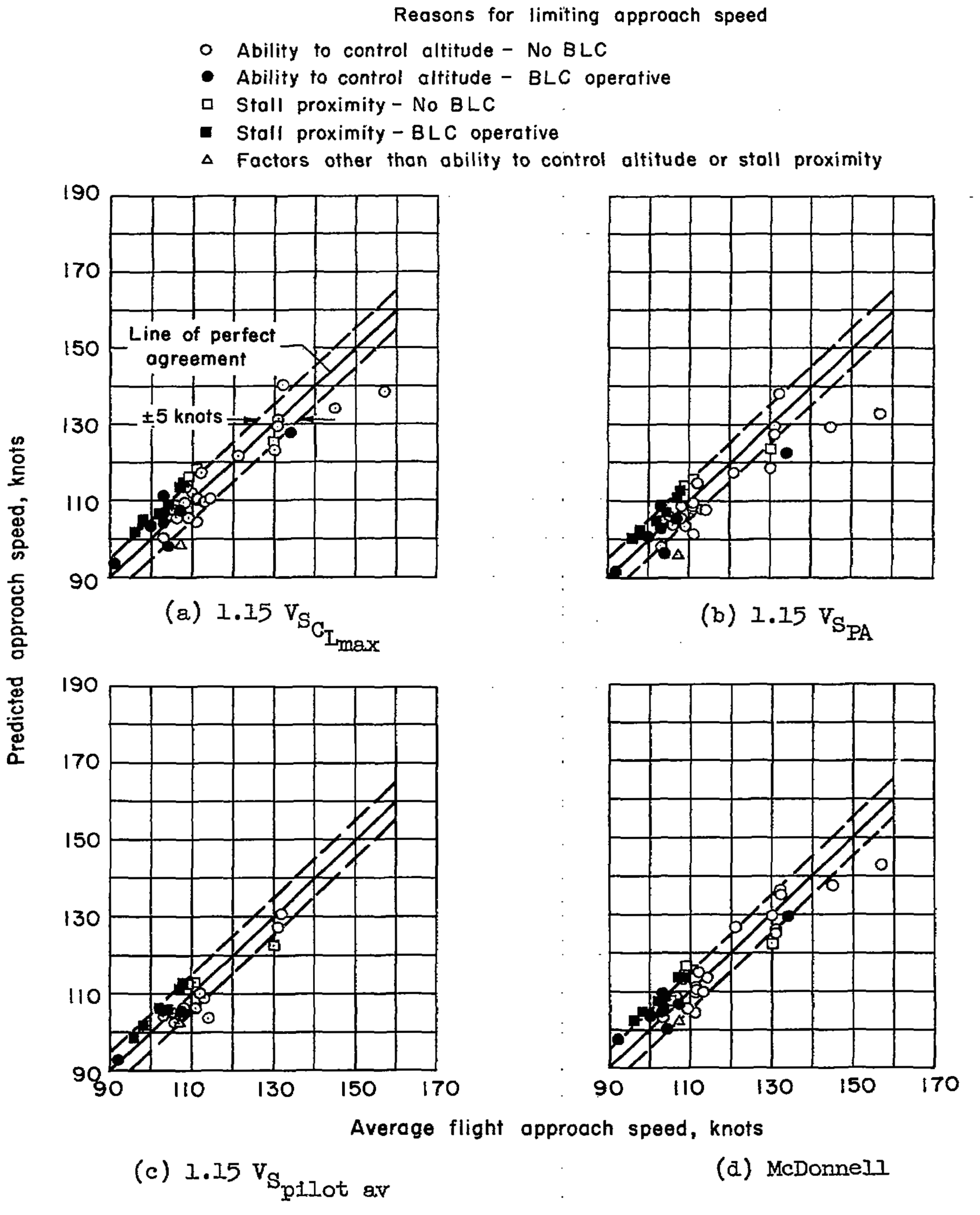


Figure 43.- Comparison of average flight approach speeds with approach speeds predicted by various criteria.

[redacted]

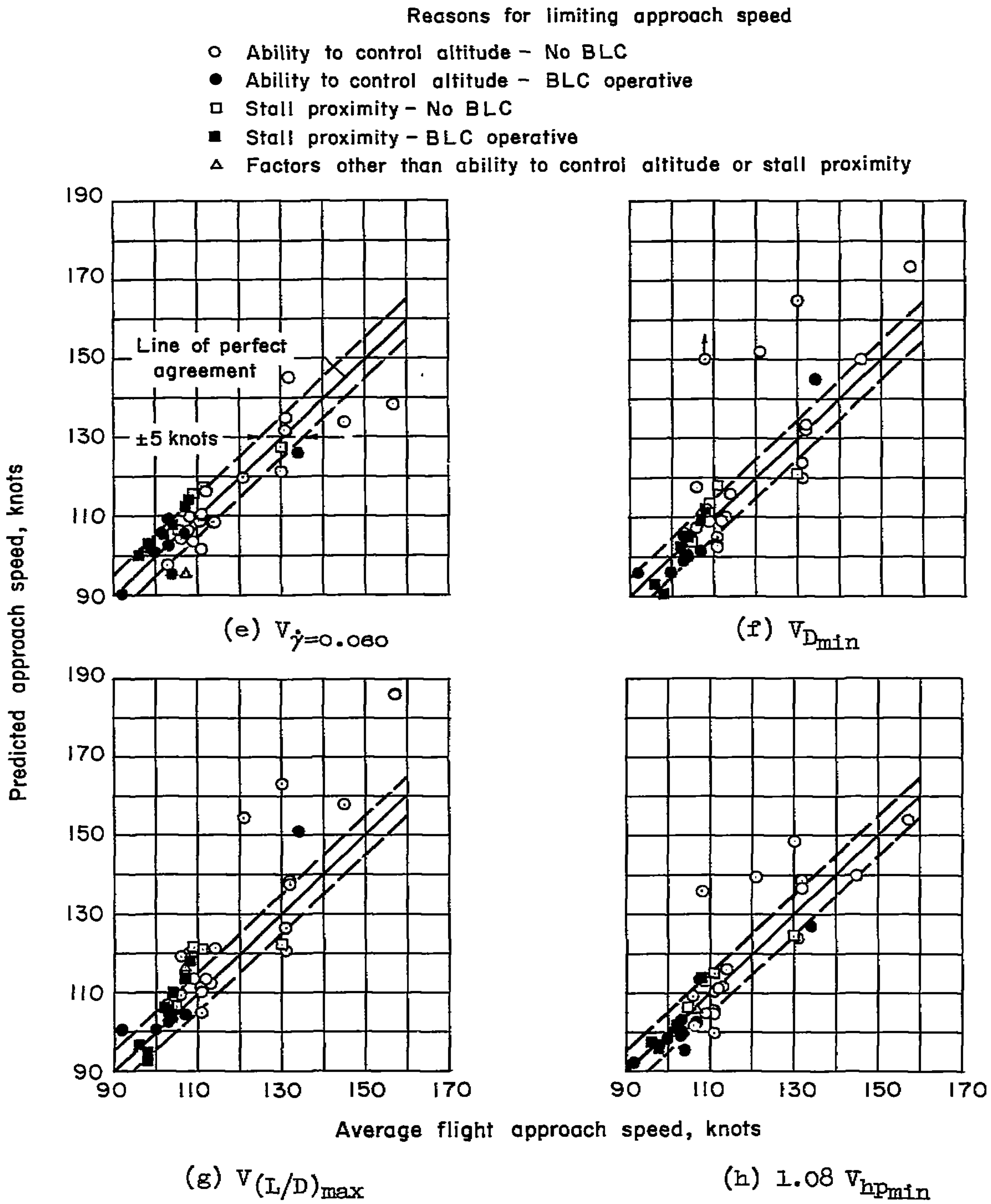


Figure 43.- Concluded.

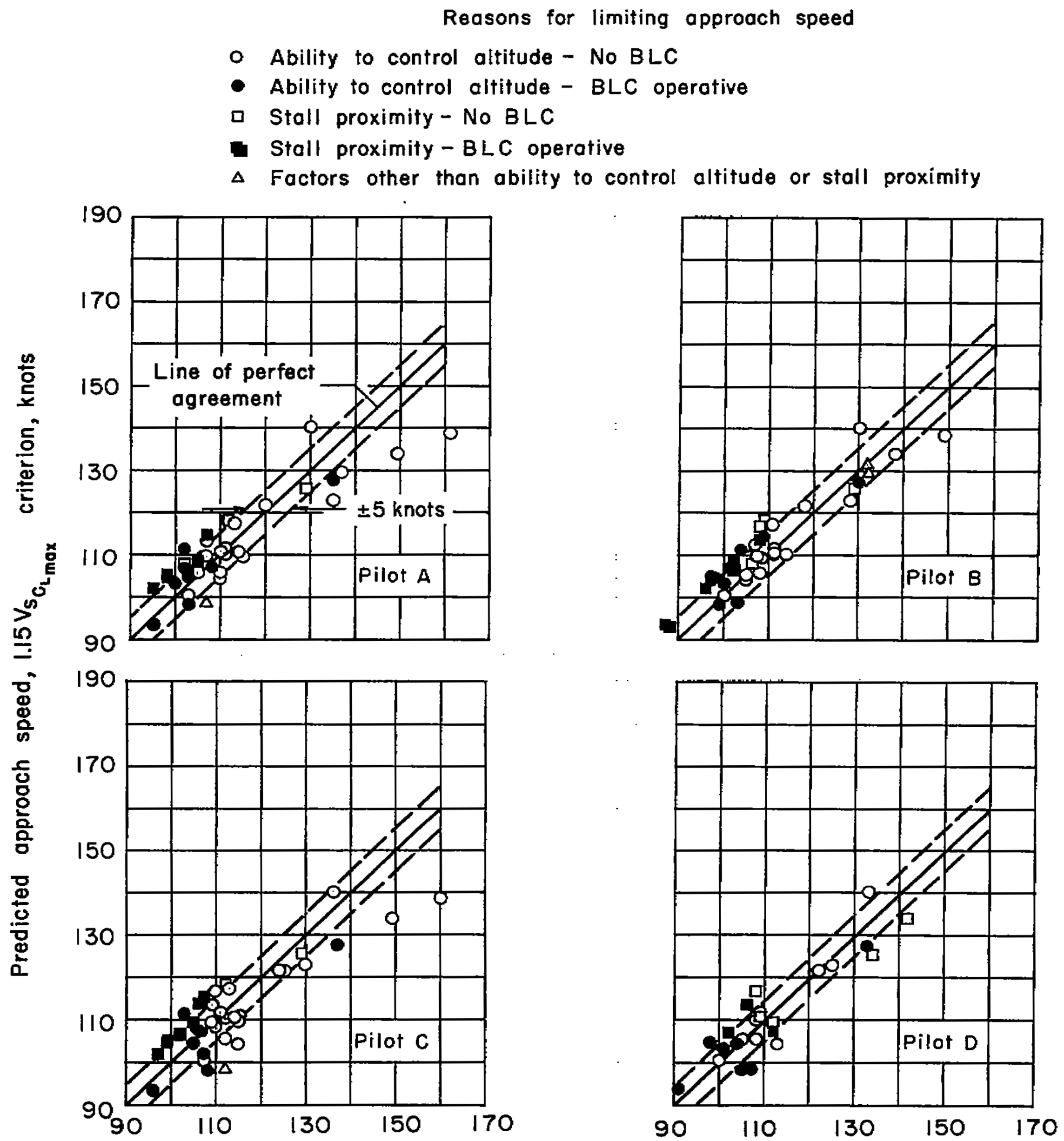


Figure 44.- Comparison of flight approach speeds for individual pilots with values predicted from 1.15 $V_{S_{C_{L_{max}}}}$ approach-speed criterion.

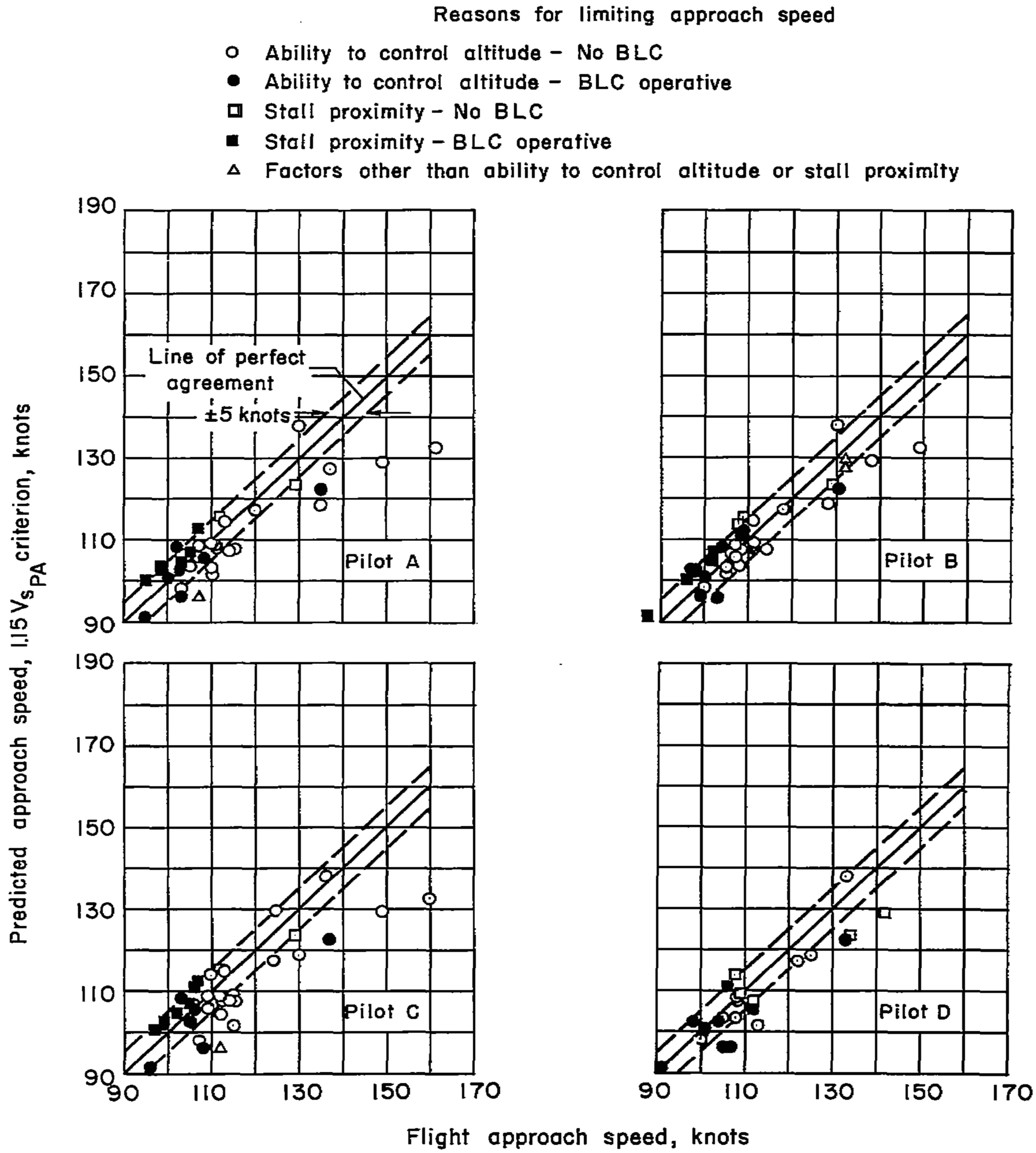


Figure 45.- Comparison of flight approach speeds for individual pilots with values predicted from 1.15 $V_{S_{PA}}$ approach-speed criterion.

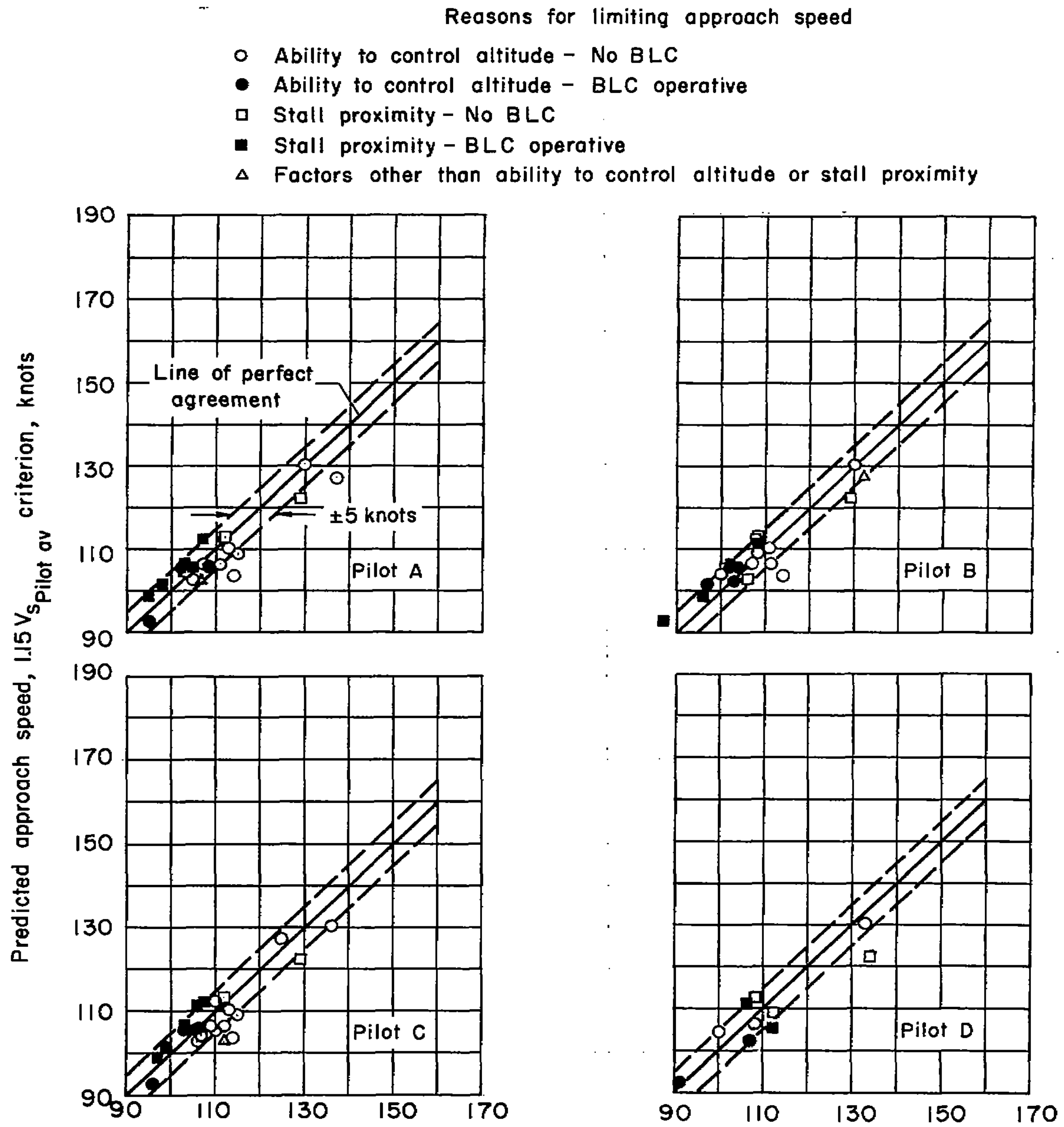


Figure 46.- Comparison of flight approach speeds for individual pilots with values predicted from 1.15 $V_{S_{pilot\ av}}$ approach-speed criterion.

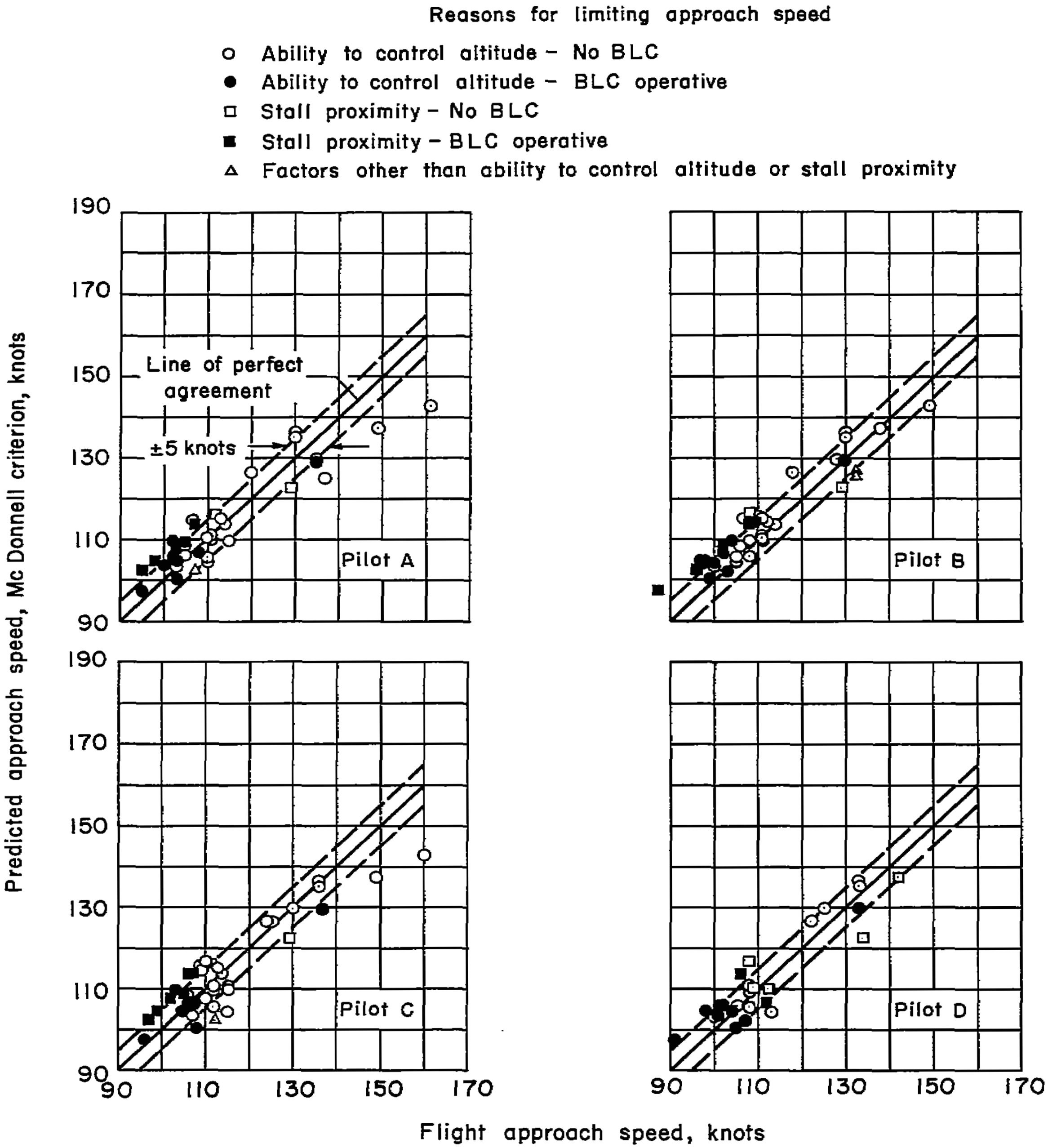


Figure 47.- Comparison of flight approach speeds for individual pilots with values predicted from the McDonnell approach-speed criterion.

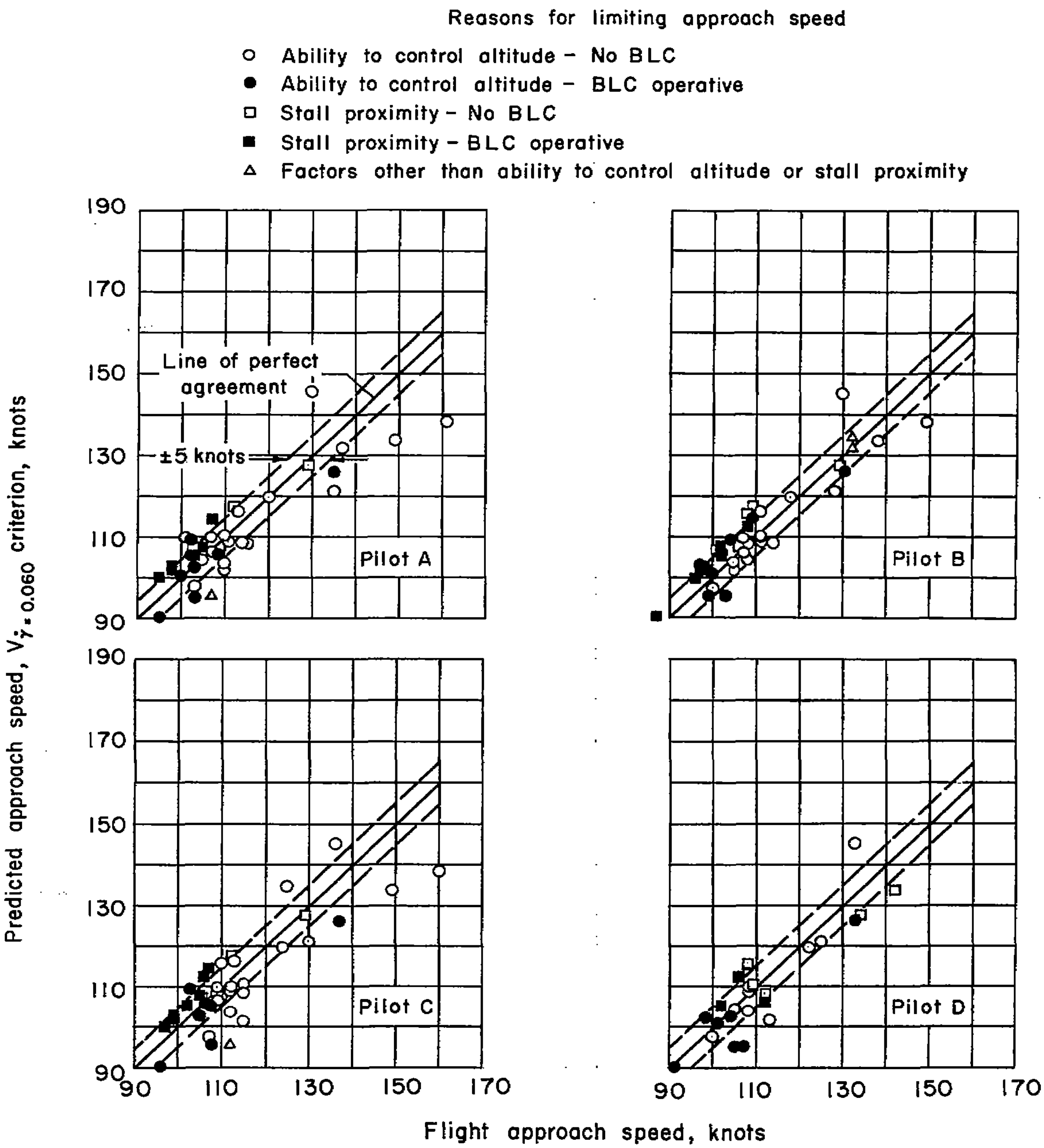


Figure 48.- Comparison of flight approach speeds for individual pilots with values predicted from the rate of change of flight-path-angle ($V_{\dot{\gamma}=0.060}$) approach-speed criterion.

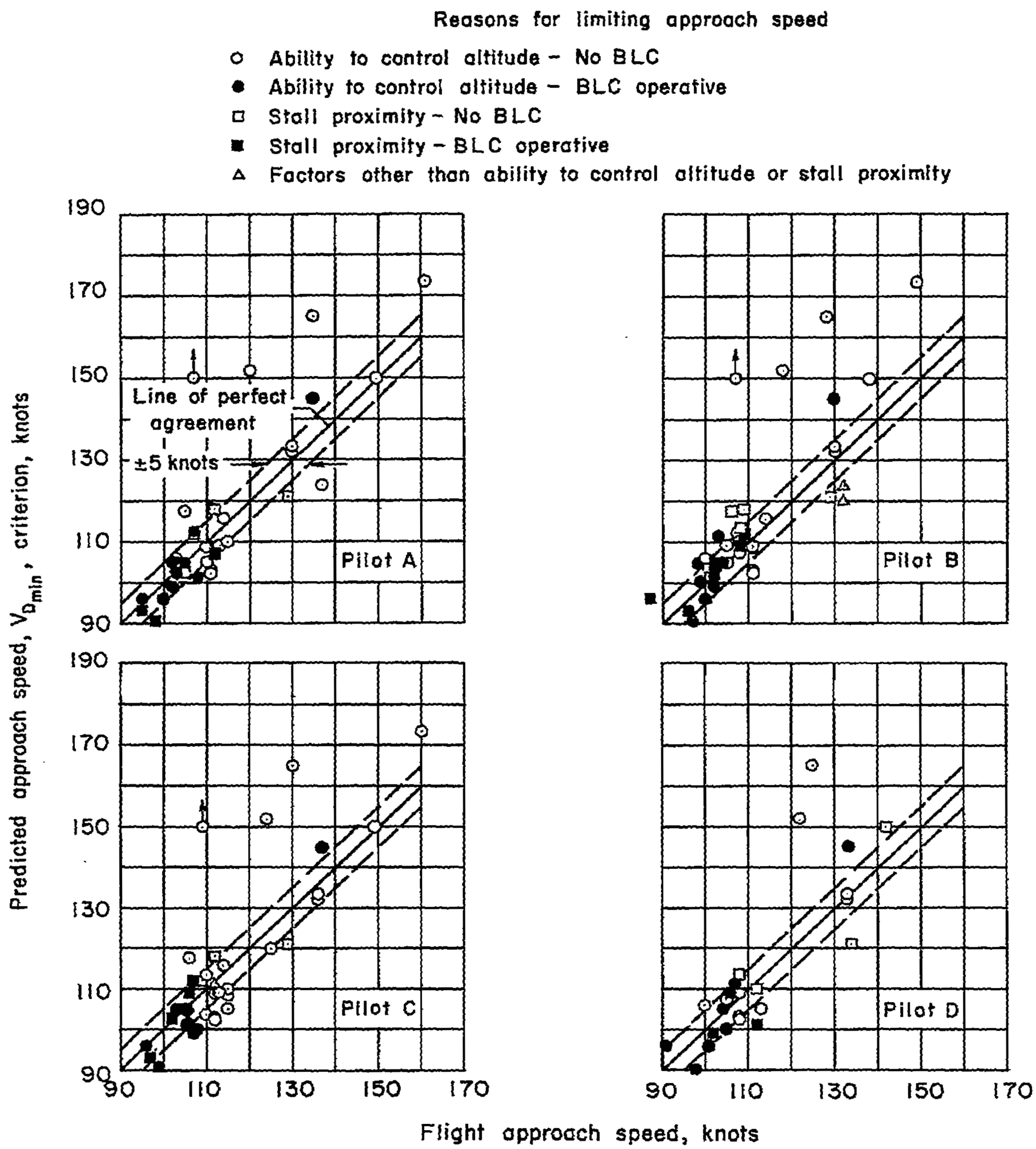


Figure 49.- Comparison of flight approach speeds for individual pilots with values predicted from minimum-drag approach-speed criterion.

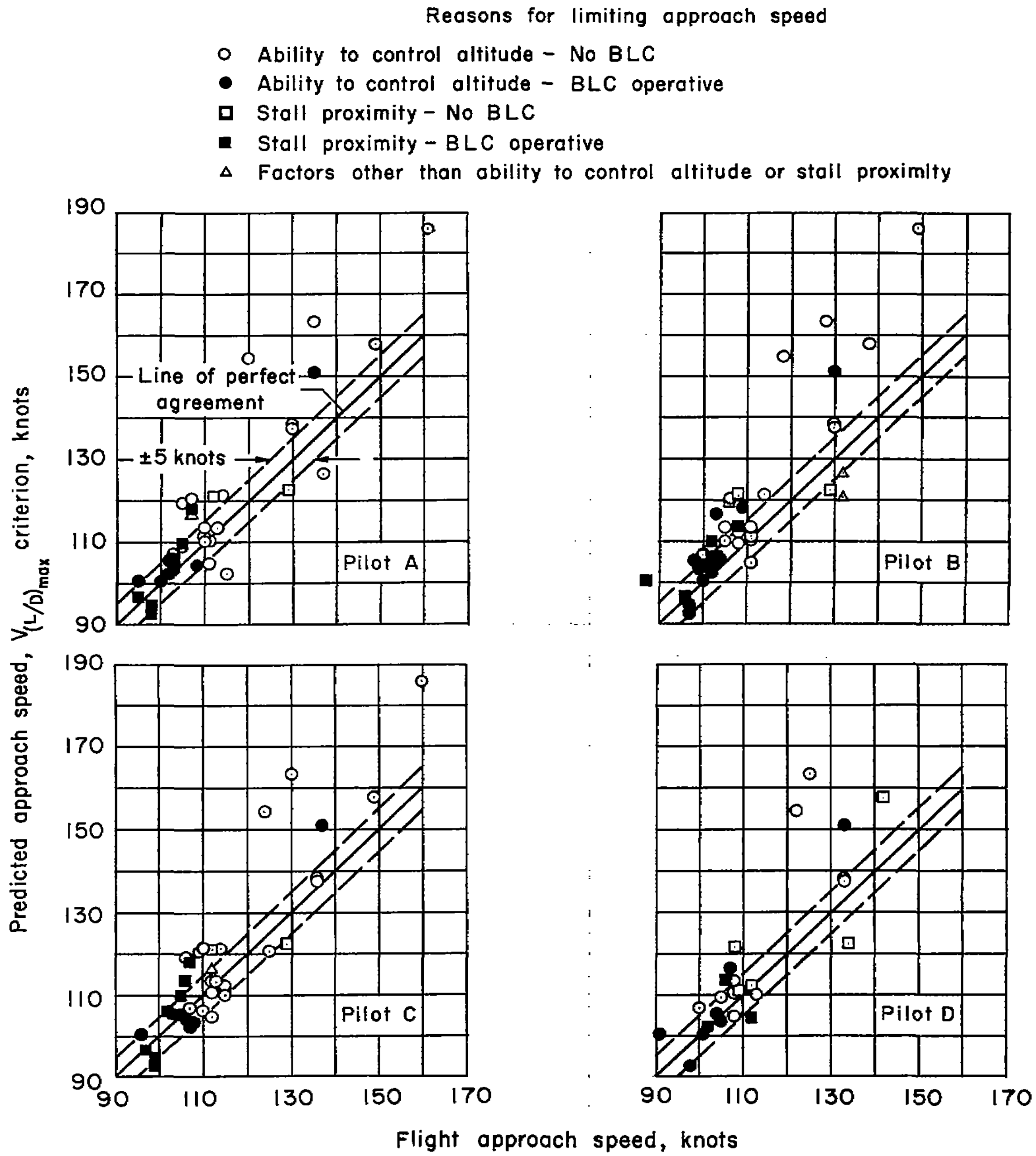


Figure 50.- Comparison of flight approach speeds for individual pilots with values predicted from maximum lift-drag ratio approach-speed criterion.

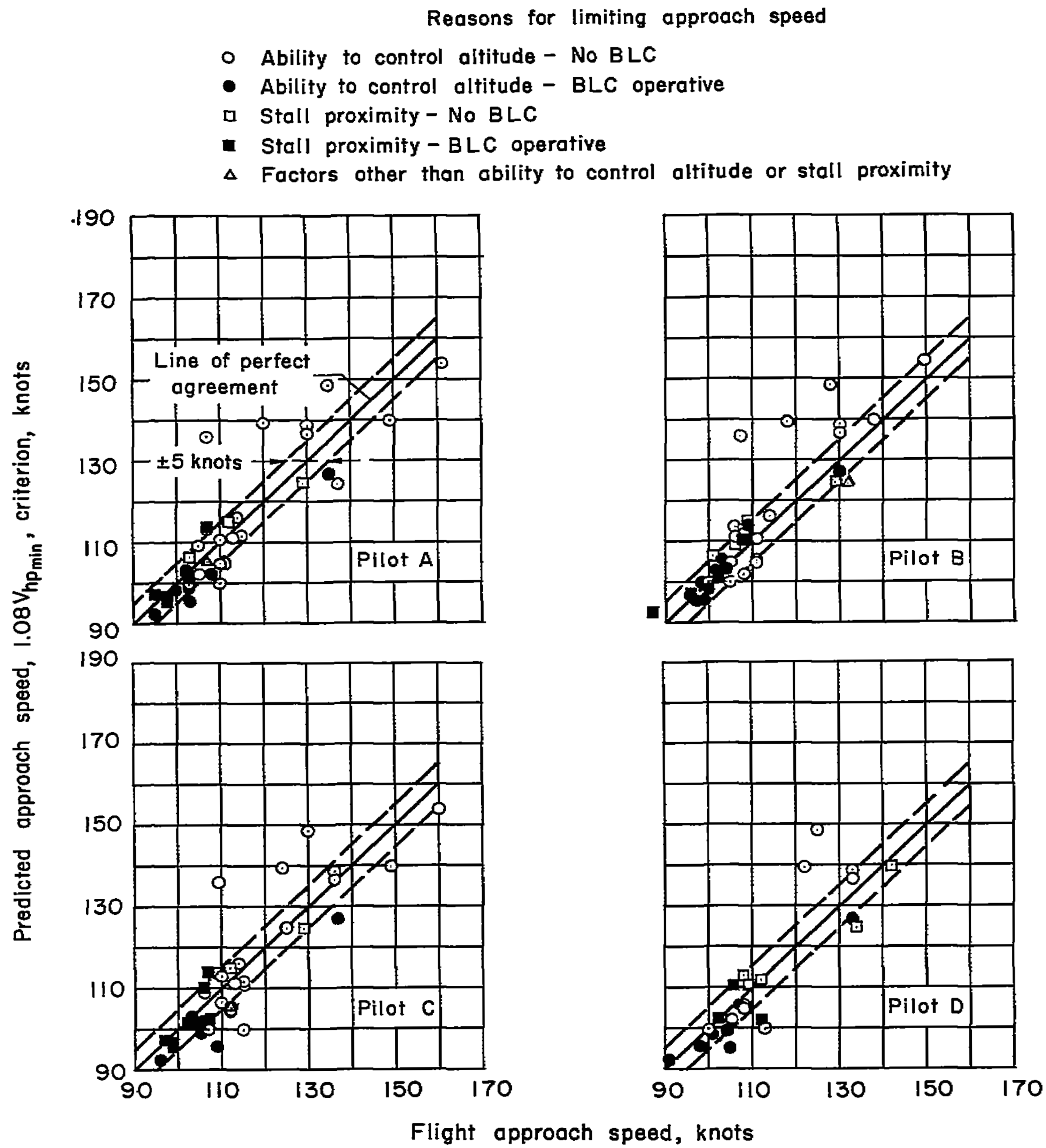


Figure 51.- Comparison of flight approach speeds for individual pilots with values predicted from minimum-horsepower approach-speed criterion.

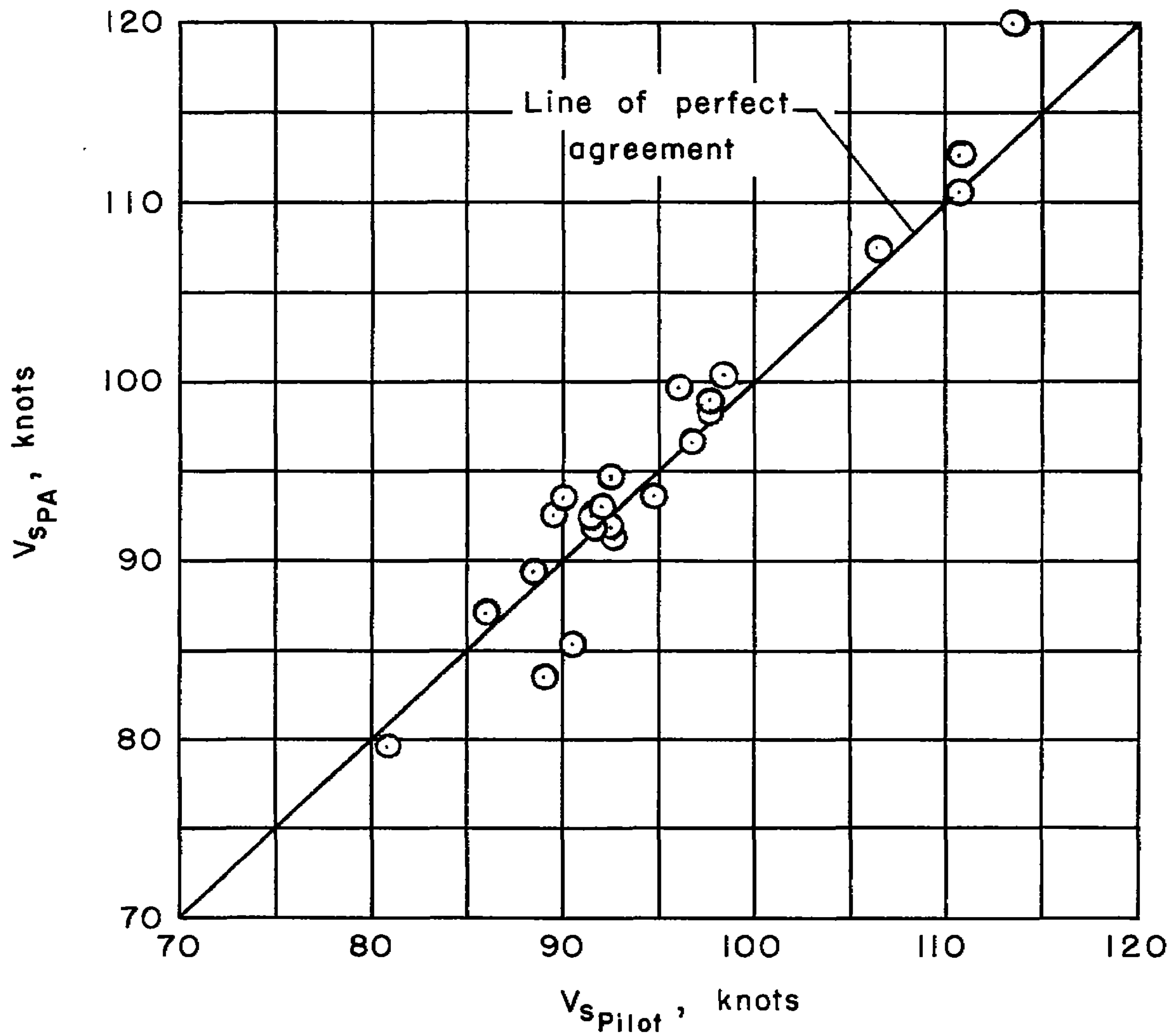


Figure 52.- Comparison of pilot-average stall speed with calculated power-approach stall speed.

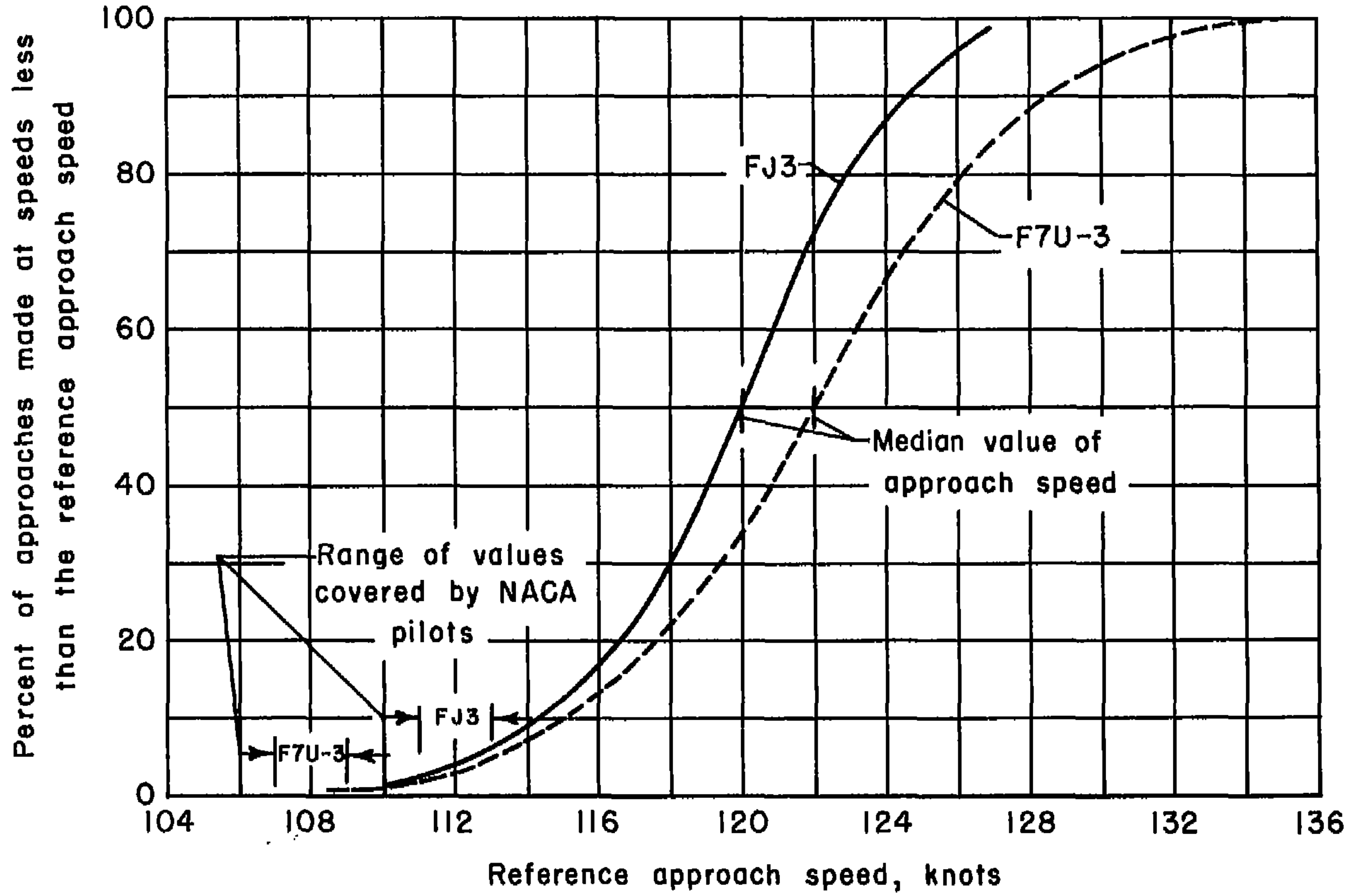


Figure 53.- Carrier landing-approach speeds used by navy pilots.

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